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Sea level rise damage produced by climate change effects

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Abstract

With global climate changing and average temperatures rising up, sea level rise have had a non-negligible impact on coastal cities. In order to be prepared for the challenges of future sea level rise, many research institutes have developed models that can predict future climate change based on carbon emissions to project climates for decades or even centuries. The RESCCUE (RESilience to cope with Climate Change in Urban arEas – a multisectoral approach focusing on water) project of the European Horizons 2020 Research is the Europe's first large-scale innovation and urban resilience project to study the climate predictions of three European cities within this century. Barcelona, as a famous coastal city, has to consider the threat of sea level rise in its impact on future development. Therefore, in order to fully understand the impact of sea level rise on Barcelona, this thesis will analyze the projection results and propose the potential impact of sea level rise in different fields. Hopefully, this thesis will let more people understand the damages of sea level rise and the impacts on our own life.

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Introduction

Climate change becomes a severer global problem that cannot be ignore in recent years. With the urbanization developing, climate change will cause more challenges and pressures to increasing population. It may obstruct cities providing continuing function services for citizens in many aspects, such as transportation, water supply, energy supply, etc. The coastal cities, as one of the most vulnerable places facing climate change, one of the big problem produced by climate change, sea level raise is receiving much more attention than before. From 1880, the sea level has been raised by 23 cm up to now and this upward trends continues with 3.3 cm per year (NASA, 2019). According to the Intergovernmental Panel on Climate Change (IPCC) says by the end of this century, there is an expectation that the sea level will raise from 26 to 77 cm with the temperature rising 1.5 degrees (National Geographic , 2019). That is enough to cause a lot of problem on global region, especially coastal cities. The sea level raise can cause really serious problem to these countries, including risk of death, injury, ill-health, coastal flooding and etc. which lead to millions life lost and trillions economic damage. Hence, lots of countries already started implement precautions to reduce the potential losses from sea level raise.

This thesis is based on four-year project RESCCUE (RESilience to cope with Climate Change in Urban arEas – a multisectoral approach focusing on water), Europe's first large-scale innovation and urban resilience project, which founded by European Union's Horizon 2020 Research and Innovation Programme. It aims to help urban areas around the world to become resilient to climate change by providing innovative models and tools to improve the abilities of cities withstand and recover quickly from stresses and maintain continuity of services.

The project is taking on three European cities, Lisbon, Bristol and Barcelona. There are six workspace in the whole project, including climate change and extreme events scenarios, strategic urban services modelling, hazard impacts and cascading effects, holistic resilience assessment and management with Hazur, resilience and adaptation strategies for the market uptake and climate-focused city resilience roadmap (RESCCUE, 2019).

The study of this thesis is focusing on Barcelona, in which the climate change is nearly a new topic. However, with the long coastal lines, nowadays it becomes an inevitable problem for Spain to consider. The main part of this thesis is analyzing the impact on infrastructures in

Barcelona city produced by sea level raise in following scenarios: 50% change level RCP 8.5 sea level rise future projection, 90% change level RCP 8.5 sea level rise future projection, current scenario with five different time return period storm surge projection, 50% change level RCP 8.5 sea level rise future projection with five different time return period storm surge projection and 90% change level RCP 8.5 sea level rise future projection with five different time return period storm surge projection. The sea level raise projection values obtained of RESCCUE project provided by Climate Research Foundation (FIC, for its acronym in Spain). All the outputs have been considered from CMIP5 (Coupled Model Intercomparison Project Phase 5).

RCP, representative concentration pathway, aiming at documenting the emissions, concentrations, and land-cover change projections. RCP8.5 is developed by the MESSAGE modelling team and the IIAS (Integrated Assessment Framework at International Institute for Applies Systems Analysis), is characterized by increasing greenhouse gas emissions over time representative for scenarios in the literature leading to high greenhouse gas concentration level (Anon., n.d.).

The purpose of this thesis is to have a general view of impact on infrastructures by sea level rise in Barcelona. Furthermore, if possible, to arisen the awareness of the damage ability of sea level rise in public and implement some necessary precaution for protecting infrastructures in the future and give a first-hand information for combining micro-economic influence in the future.

According to reach the purpose, the following sections will be described in this thesis:

1. Describing the study area, including its location, geography, meteorology and economic structure.
2. Summarizing the whole RESCCUE project task have been finished for now, including the original data obtain, projections in 2 future scenario current scenario plus storm surge events and 2 future scenarios plus storm surge events. All of the projection just extracts the result under RCP 8.5 scenario in 2100.
3. The most important section is analyzing the result gained from modelling simulations, the above mentioned five scenarios will be analyzed.

4. According to the doubts and errors in the results map, it is worthy to modify the result to get the more accurate results. Hence, the correction results based on field trip will be generated.
5. After analyzing and the correction, a summary of impact will be discussed by three type of areas. The impacts are not only including the physical influences that clear showing in the results map, but also the potential impacts in other aspects, such as economy, tourism, heritage and cultural protection, irrigation and human security.
6. Based on the limitation of analysis, a discussion and suggestion would give at the last of thesis in order to improve this study in the future.

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Recent studies on climate variable at Barcelona

From the last century, the studies on climate change is gradually becoming a hot topic. There are some papers show the results of research on this topic, this paper will focus on the part of sea level rise.

For temperature, during 1917 to 1998, there is a significant trend that the mean maximum temperature has a change of +1.4 ℃/100year at the observatory of Fabra (Barcelona). Especially in autumn and winter period, the increased value can reach to +2.0 ℃/100year (Serra C., 2001).

Regarding to sea level, between 1992 and 2009, there is a greater consensus for sea level rise. It was presented an increase of +5.58±0.15 mm/year (Montañés, 2012). And from 1993 to 2011, the increase is about +6.6 mm/year (Montañés, 2012).

For future sea level, projections show Barcelona could suffer a rise of the sea level of 1.3±0.3m at the end of century (Fernández, 2016). This increase is slightly lower for the lowest scenarios (about 0.8 m) and it is almost double (up to 2.4 m) under the highest scenario of some models (Pfeffer, 2008). All these projections are much greater than the observed trend at recent years (Montañés, 2012) (Fernández, 2016).

As can be seen from the papers mentioned above, sea level rise situation has a serious trend year by year, which is an imminent threat to the coastal city of Barcelona. In order to better understand the impact of sea level rise over the next 100 years, this thesis will analyze the simulation results from the latest sea level rise projection.

Methodology

Study area

Location and Geography

Barcelona, as the capital of the autonomous community of Catalonia and the second most populous city in Spain, located on the Mediterranean coast 41°23′ N/ 02° 12′ E. It has about 15 km coastal line including harbors and beaches on a nature border plain from Llobregat river to Besós river. The city has five small hills, Monterols, Putxet, Carmel, Rovira and Peira. The promontory of Montjuïc is by the coast, rising to a height of 191.7 meters.

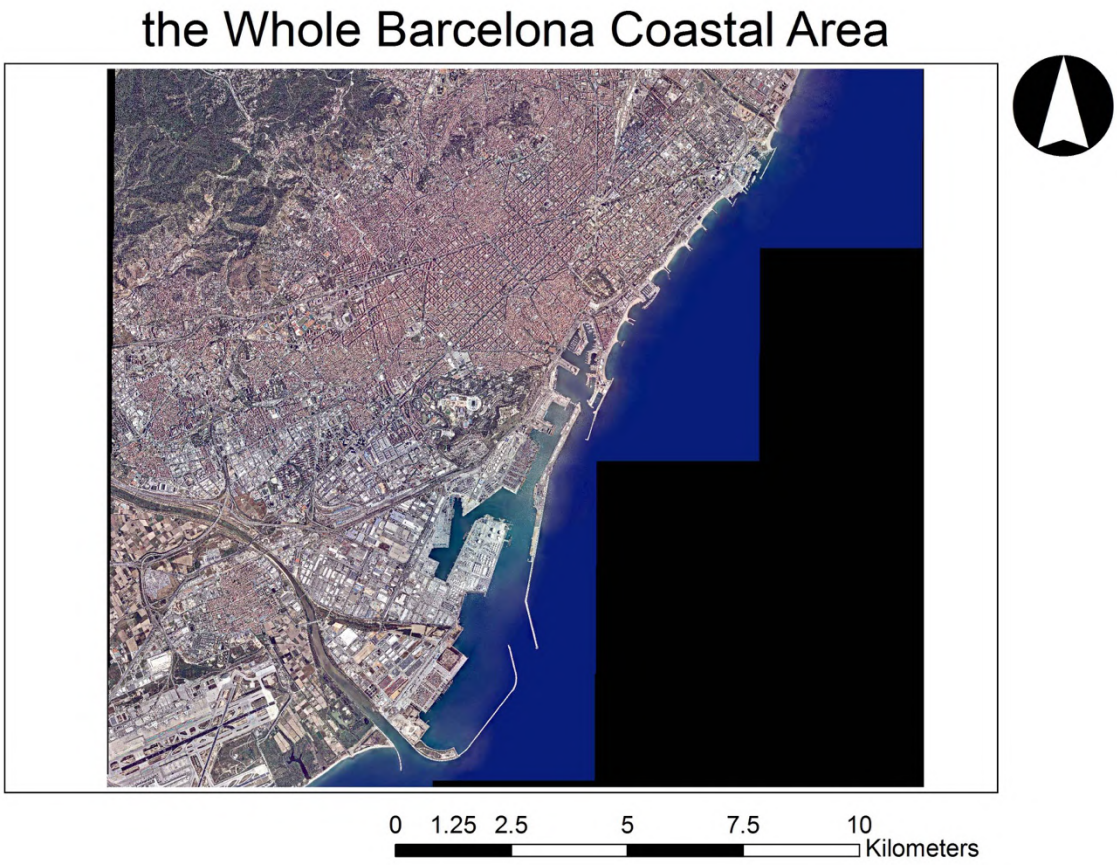

Figure 1. The satellite image of study area

Sea level rise will impact all of these activities with this area without doubt. Hence, the study on sea level rise effect in Barcelona city is important to maintain the sustainable urban development.

Meteorology

The city of Barcelona has Mediterranean climate with maritime influences. During summer, the weather is hot and dry, and it is warm and wet during winter. The precipitation is mostly concentrated in spring and autumn reaching a total of 598mm/year and average temperature is about 16.5℃ with 2483 hours of sunshine. A high intensity with short duration and high spatial variability rainfall pattern is recent rain events in Mediterranean area. It is really frequently that 50% of the annual precipitation occurs during few rainfall events.

Economic structure

Barcelona is a compact settlement, there is a population of 1,619,337 inhabitants on the area of 100.4 square kilometers, which implies a density of 15,570 inhab. /km^2.

In the history, thanks to the wonderful geographical location, the economy in Barcelona is based on maritime trade. After industrial revolution, the city became an important center for the production of textiles and machinery. By the benefit of its location, the traditional art, the nature ports and beautiful beaches, also because of the limitation on high price of industrial land, Barcelona convert its economy focus from industry to services, especially in trade, catering and tourism.

Data Collection and Model

The Spanish State Meteorology Agency provides climate change scenarios for Spain based on CMIP5 climate models in order to obtain local projections of precipitation, temperature and sea level rise, storm surge and heat wave. There are ten climate models included (ACCESS1-0, BCC-CSM1-1, CanESM2, CNRM-CM5, GFDL-ESM2M, HADGEM2-CC, MIROC-ESM-CHEM, MPI-ESM-MR, MRI-CGCM3 and NorESM1) (R.Monjo, 2016). In the case of Sea Level Rise projection, there are totally nine models are included due to the fact that the model BCC-CSM1-1 was neglected during the control quality process.

In order to study on the changes in future extreme values, a baseline was required to compare the simulated and observed data in the past periods. The buoy can be used for obtain the observed data for sea level rise is from 1993 to 2016, for storm surge is from 1994 to 2016. Hence, several statistical downscaling methods would be applied in CMIP5 models to extend the baseline data. The downscaling methods were verified using the ERA-Interim re-analysis as a reference for reproducing the past climate (R. Monjo, 2017). In the case of Sea Level Rise, the baseline period has extended to 1850-2005, as well as for storm surge and wave height. The same period from 1979 to 2015 was fixed as for all the variables. Regarding the period taken as a historical reference to find the variations, the same has been taken throughout the RESCCUE project: from 1986 to 2015.

Simulation

The RESCCUE projection use following approach to obtain the future projections. In order to obtain our most interested result, the synthetic extreme (SE) events is defined to present the most interested events. Each SE is defined according to a particular return period (R. Monjo, 2017). The approach is performed in two steps: firstly, it is obtained the projected change in the SEs for each future period (2011-2040, 2041-2070 and 2100) with respect to the baseline (1986-2015). Secondly, it is obtained reference SEs based on extended observations for the same period and then the projected change is applied. In this thesis, all the analysis will base on the future period 2100 projection.

Uncertainty

There are three factors can affect the extreme events simulation: the method-model performance; the RCP scenarios considered and the climate natural variability. For the last two uncertainty, they are always represented using the ensemble strategy and the ensemble

projections is presented by using uncertainty area. Particularly, it is considered the 10th-90th percentile values and the median value for each year- horizon, calculated from all stations and models validated for each climate variable. In this thesis, the analysis will only extract the RCP8.5 result under 50 percentile and 90 percentile.

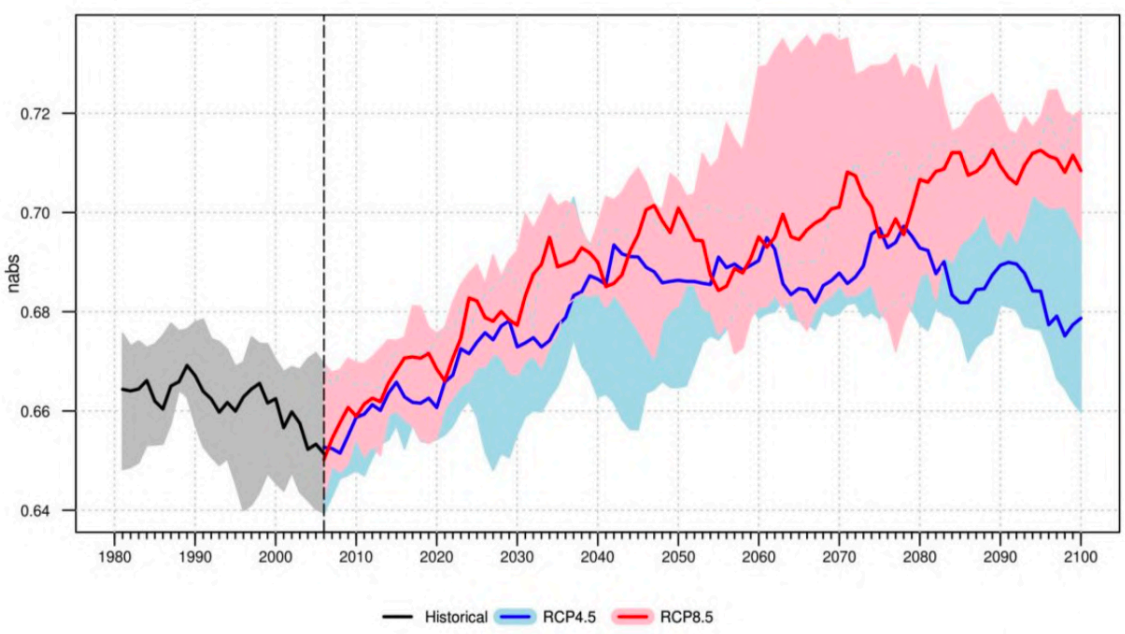

Figure 2. Example of ensemble strategy for derived variables. Panel shows climate projections of changes in the n-index for a random city. The ensemble median (solid lines) and the 10th-90th percentile values (shaded areas) are displayed. The vertical dashed line marks the end of the Historical data. (2005) (R. Monjo, 2018)

Analysis steps

Following the objectives, the main section in this thesis is analysis. The analysis will be divided into two parts: Sea Level Rise projection analysis and combined projection analysis (Sea Level Rise and Storm Surge). All the analysis based on the CMIP5 models simulation. Due to the small inaccuracy of the Digital Elevation Model, a limited correction will be proposed based on an individual field trip. At the end of analysis, an impacts summaries will give a potential influence produced by projections in city, river and coastal area domain.

Analysis

Result description

Sea level rise projection

According to the climate and decadal projections, it shows that the mean sea level of Barcelona has a possible decrease due to the salinity in the Mediterranean Sea (Tsimplis MN, 2002). And the median simulations projected a slight sea level rise about 5cm/century, with a maximum up to 30 cm/century according to RCP8.5 scenario. One can say there is no significant changes are expected for Barcelona since it with a high-level uncertainty. In fact, this uncertainty is reflected by the recent satellite-based observation from 1992 to 2014, which shows the sea level rise less than 20 cm/century and even negative in Barcelona sea, up to -10 cm/century. In this thesis, according to the results from nine CMIP5 models, the median simulation projection of 5 cm/century will be taken as 50 % percentile result, and the maximum situation 32 cm/century as 90 % percentile result for the projection in 2100 under RCP8.5 scenario.

Combined projection: three scenarios + storm surge

The result of combined projections is calculated manually, which is, the current scenario (the baseline), the 50% sea level rise scenario and 90% sea level rise scenario plus different return period storm surge results respectively. The probability of storm surge occurrence is taken from the following return periods: 1, 10, 50, 100 and 500 years. And the results show as following:

Table1. Combined projection results

Return Period	Current Scenario (1986-2015)	Future Scenario (2100)	
		50% SLR + Storm Surge	90% SLR + Storm Surge
T1	0.46	0.05+0.51=0.56	0.32+0.68=1.00
T10	0.67	0.05+0.74=0.79	0.32+0.9=1.22
T50	0.87	0.05+0.94=0.99	0.32+1.1=1.42
T100	0.97	0.05+1.07=1.12	0.32+1.24=1.56
T500	1.24	0.05+1.31=1.36	0.32+1.64=1.96

*Note: the unite of table is meter

Geographical partition

In order to more accurate analysis, the whole Barcelona coastal area will be divided into 13 parts for careful description, including:

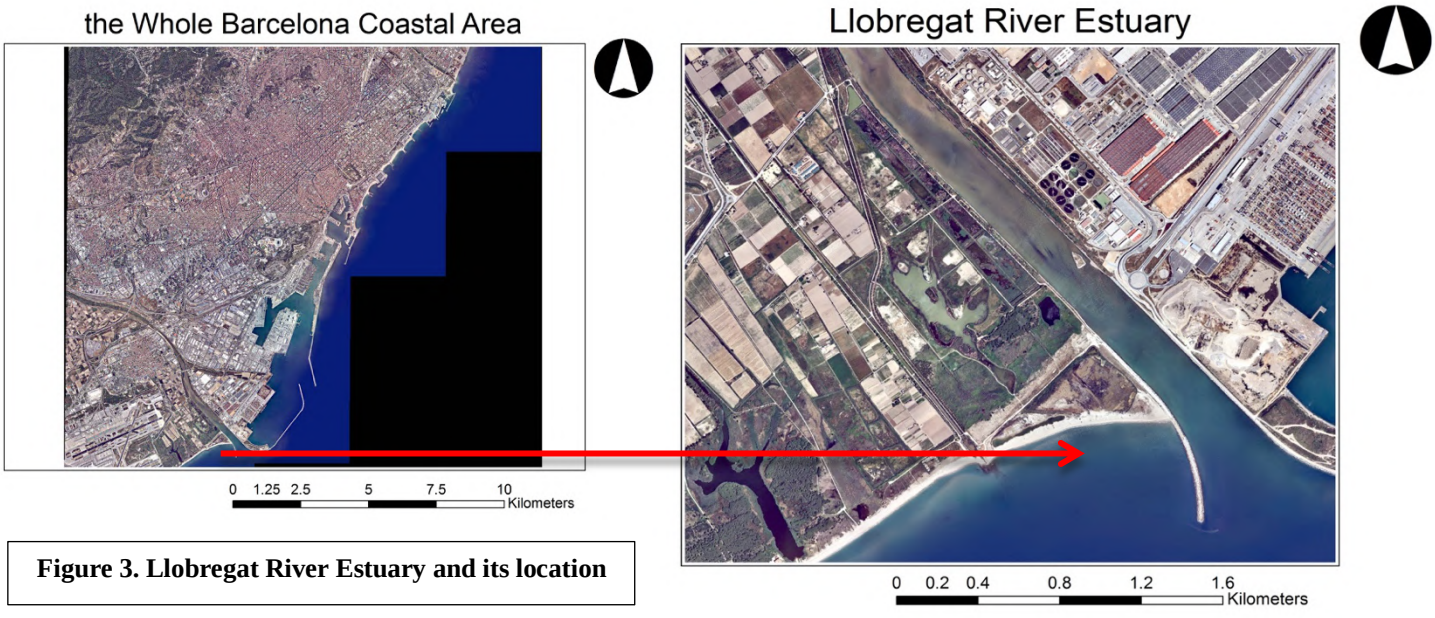

Figure 3. Llobregat River Estuary and its location

Llobregat Estuary: focusing on the green space and beach of Llobregat river right bank;

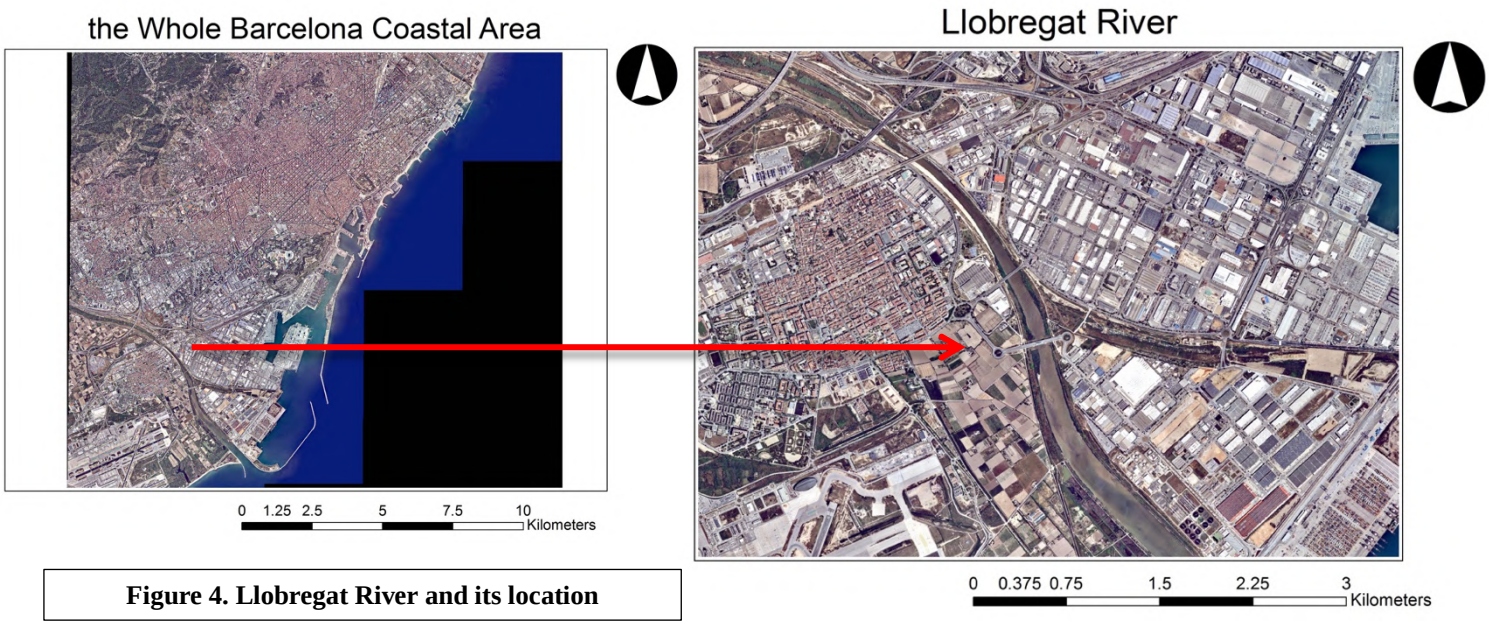

Figure 4. Llobregat River and its location

Llobregat River, including the whole river located within Barcelona city, focusing on the influences on the both banks;

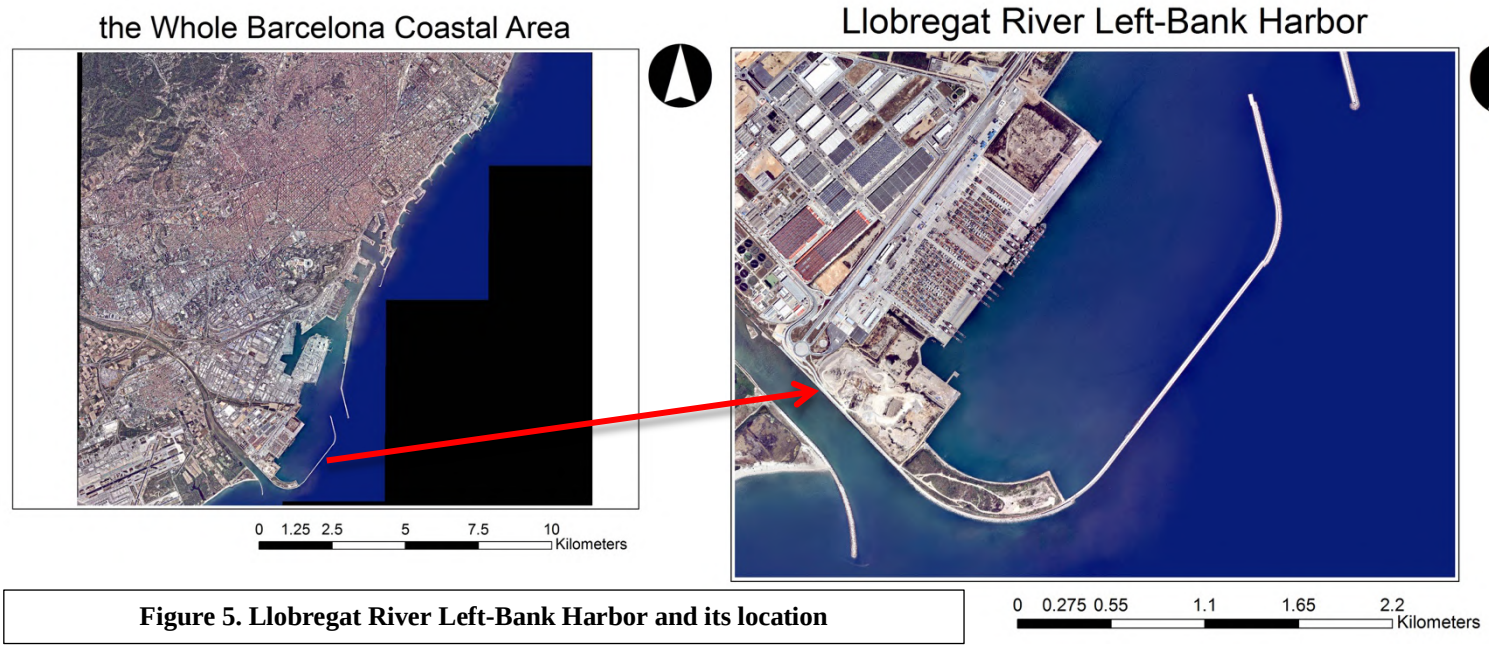

Figure 5. Llobregat River Left-Bank Harbor and its location

Llobregat River Left-Bank Harbor, which located at the left of the Llobregat river estuary to the end of the breakwater surround this harbor;

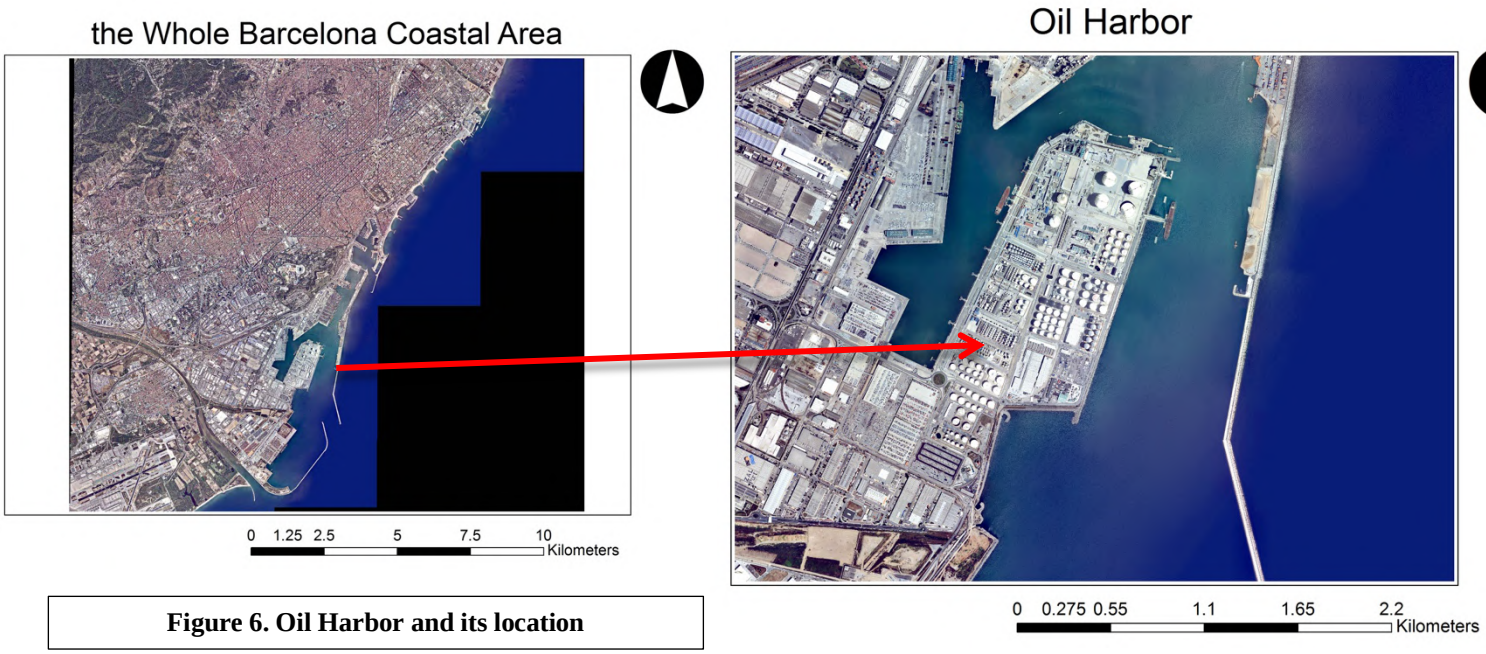

Figure 6. Oil Harbor and its location

Oil Harbor, named after the giant cylindrical oil drum, including the trade port de Barcelona and one part of breakwaters on its east;

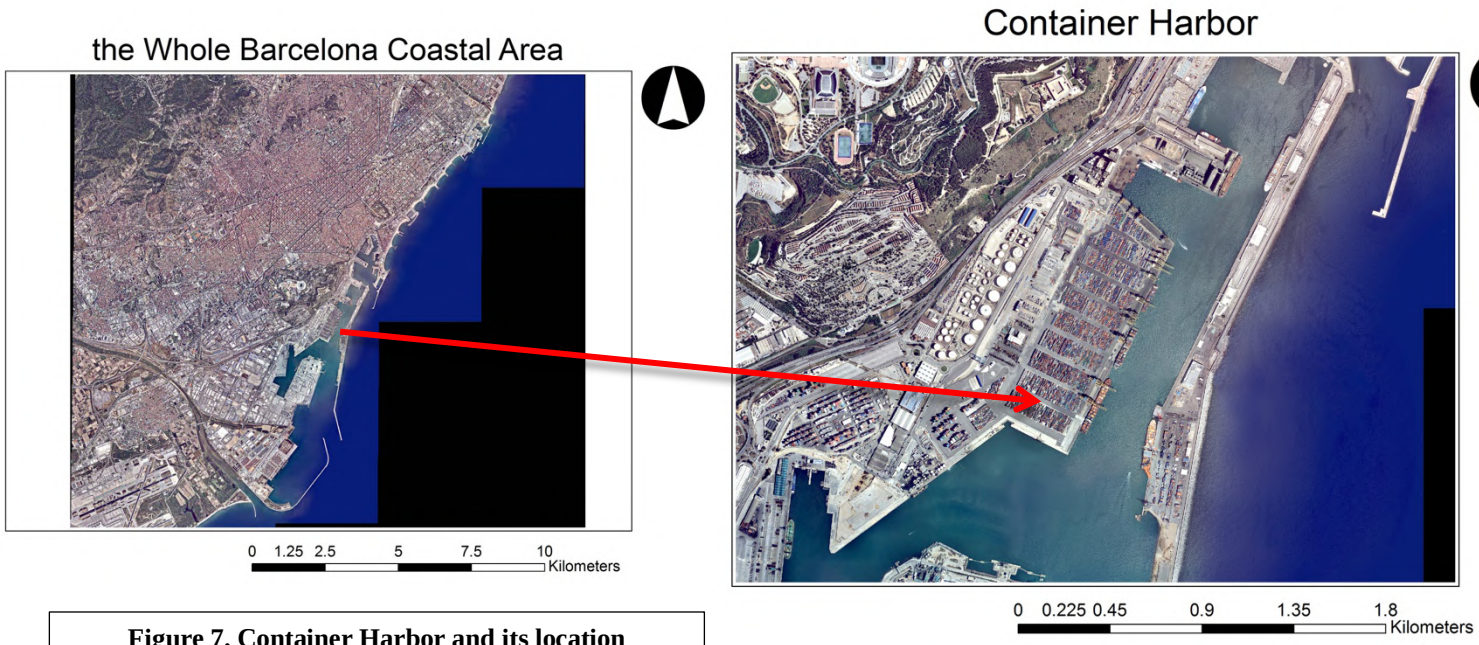

Figure 7. Container Harbor and its location

Container Harbor, named after the container on the docks, backed by Montjuïc mountain and including the ports surround the main harbor;

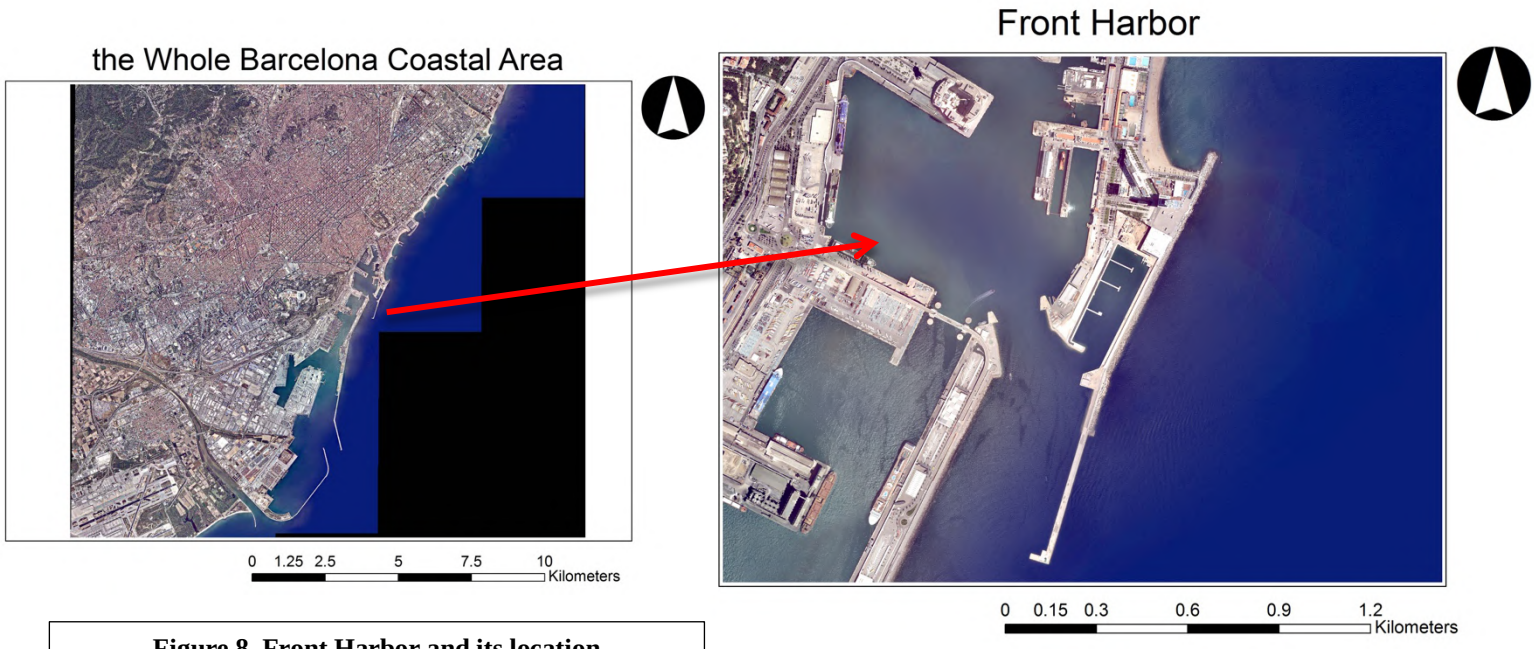

Figure 8. Front Harbor and its location

Front Harbor, named after being the front location compare to other harbors, including the yacht port, repairing dock and the part which W hotel located;

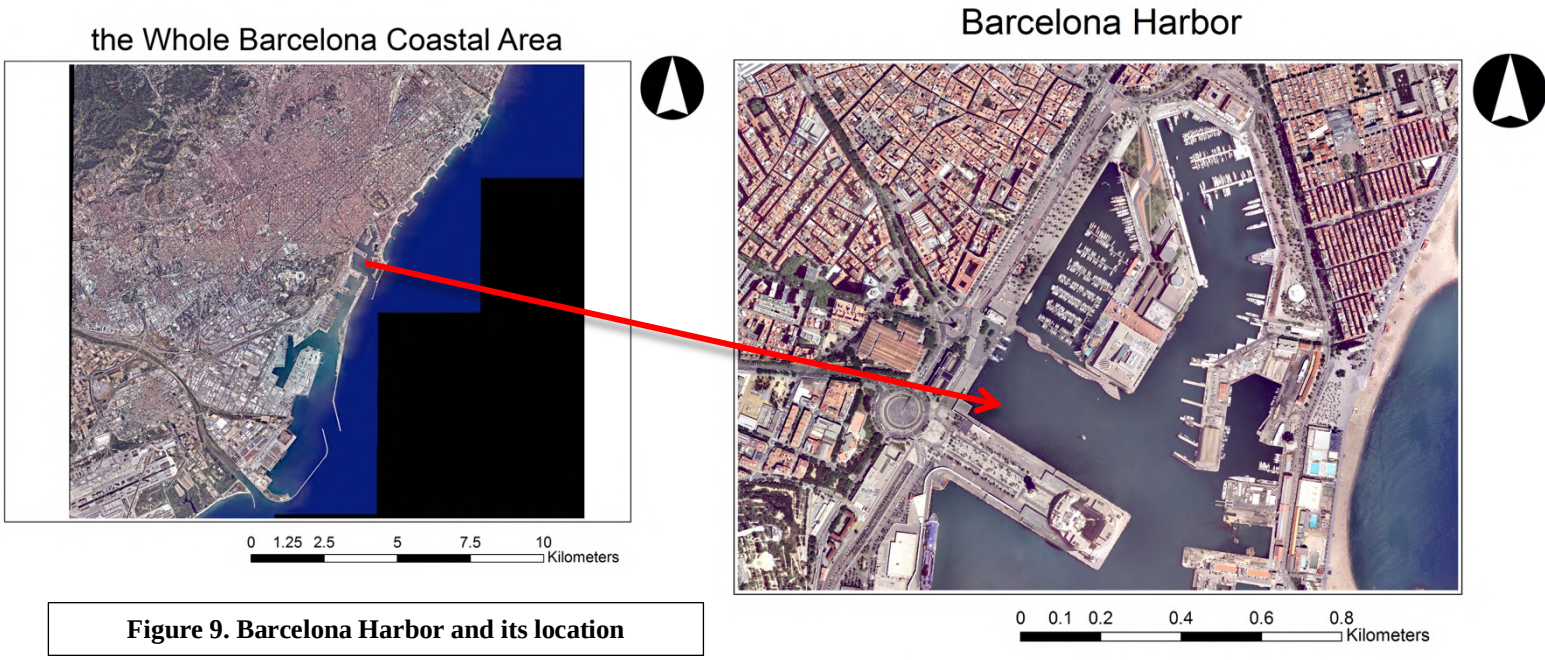

Figure 9. Barcelona Harbor and its location

Barcelona Harbor, beginning from Mirador of Colom to the Front Harbor, including yacht ports, repairing zone, all the ports commercial places and visiting places within harbor;

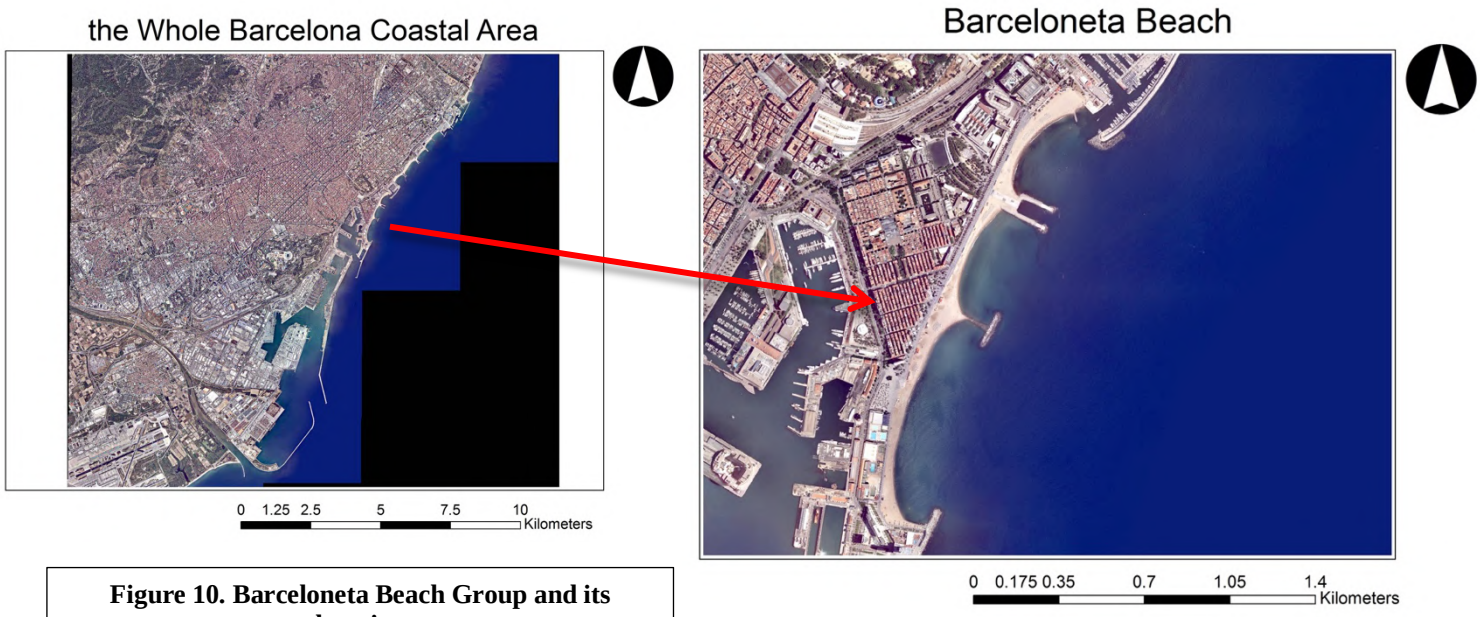

Figure 10. Barceloneta Beach Group and its location

Barceloneta Beach Group, including four beaches, which are Sant Sebastià beach, Sant Miquel beach, Barceloneta beach and Somorrostro beach from W hotel at southwest to the Olympic Harbor on the northeast;

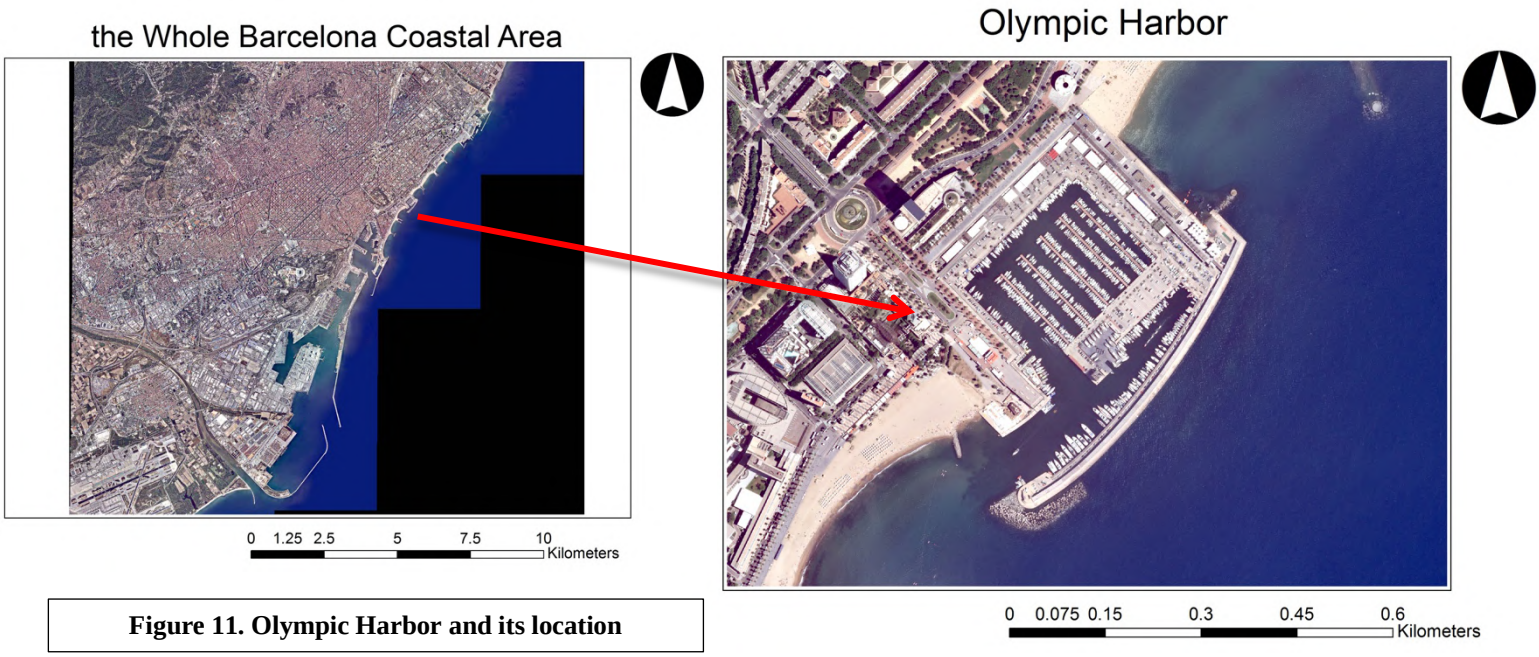

Figure 11. Olympic Harbor and its location

Olympic Harbor, including the whole harbor and surrounded breakwaters;

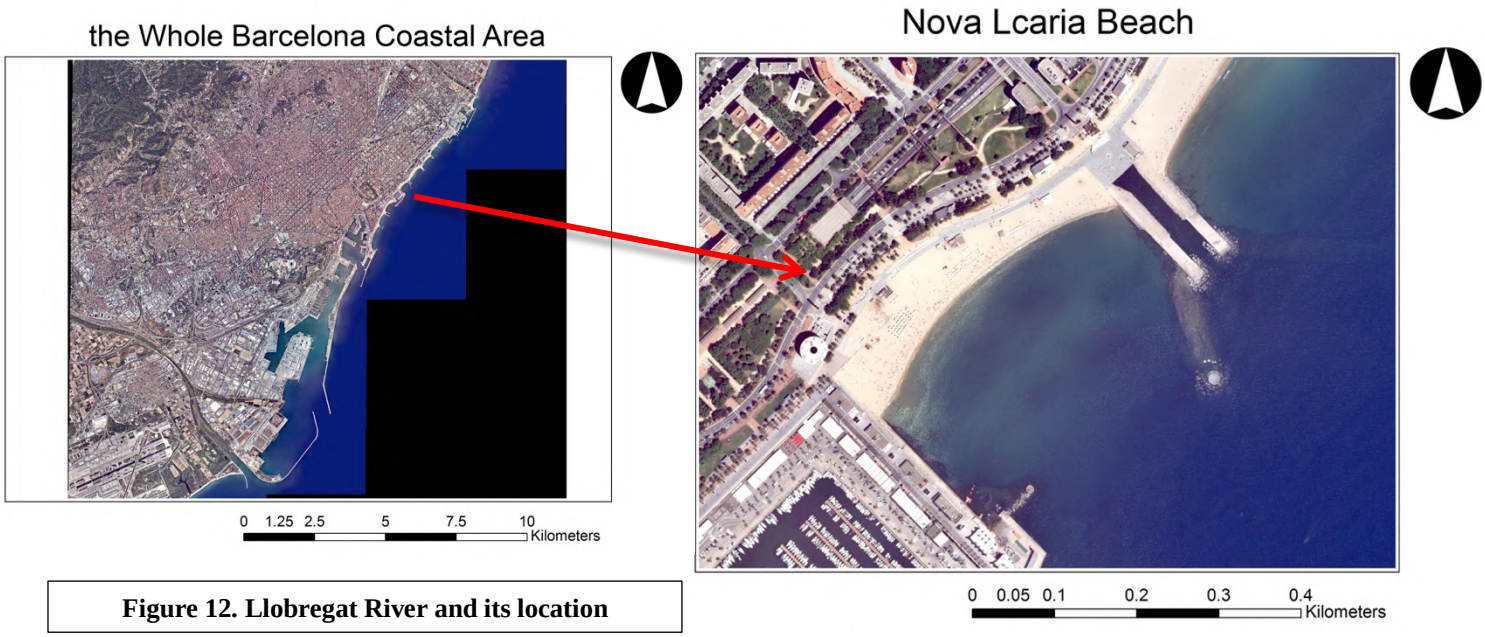

Figure 12. Llobregat River and its location

Nova Lcaria Beach, the beach located on the east of Olympic Harbor;

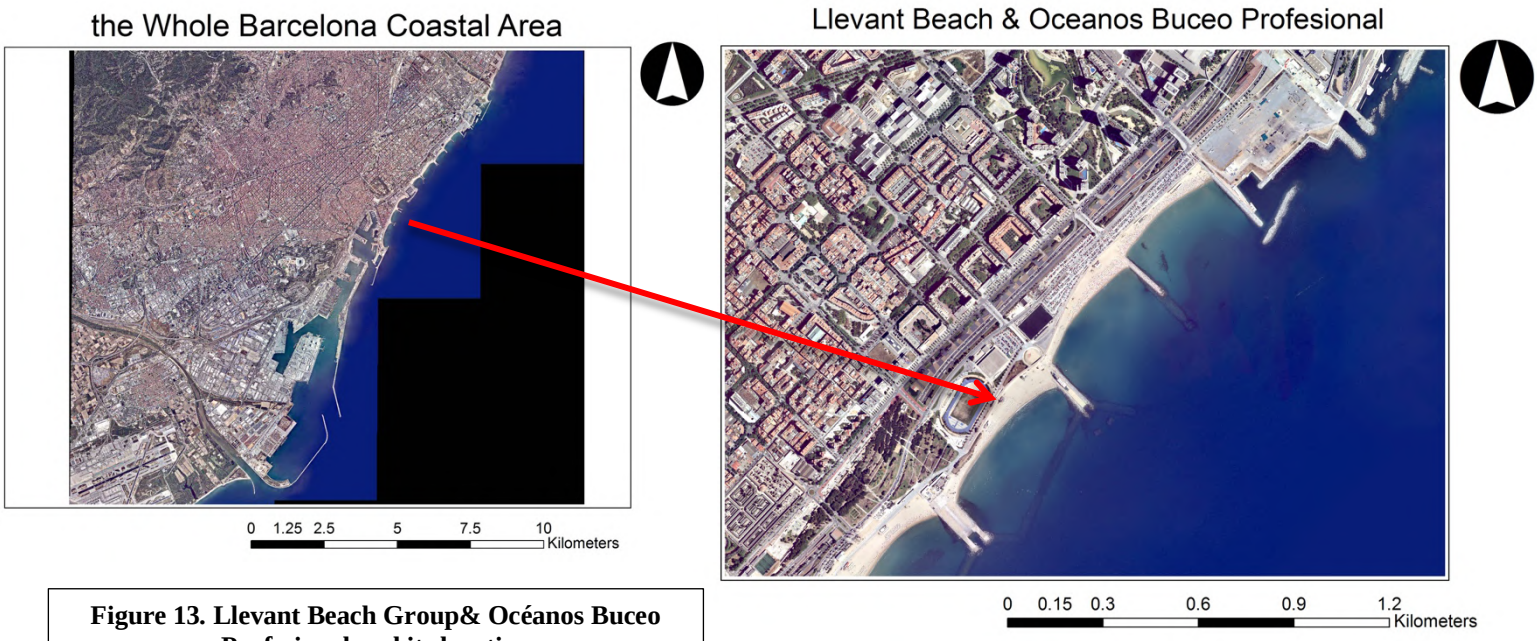

Figure 13. Llevant Beach Group& Océanos Buceo Profesional and its location

Llevant Beach Group& Océanos Buceo Profesional, including three parts of beaches named La Mar Bella beach, La Nova Mar Bella beach and Llevant beach, plus the professional ocean diving zone;

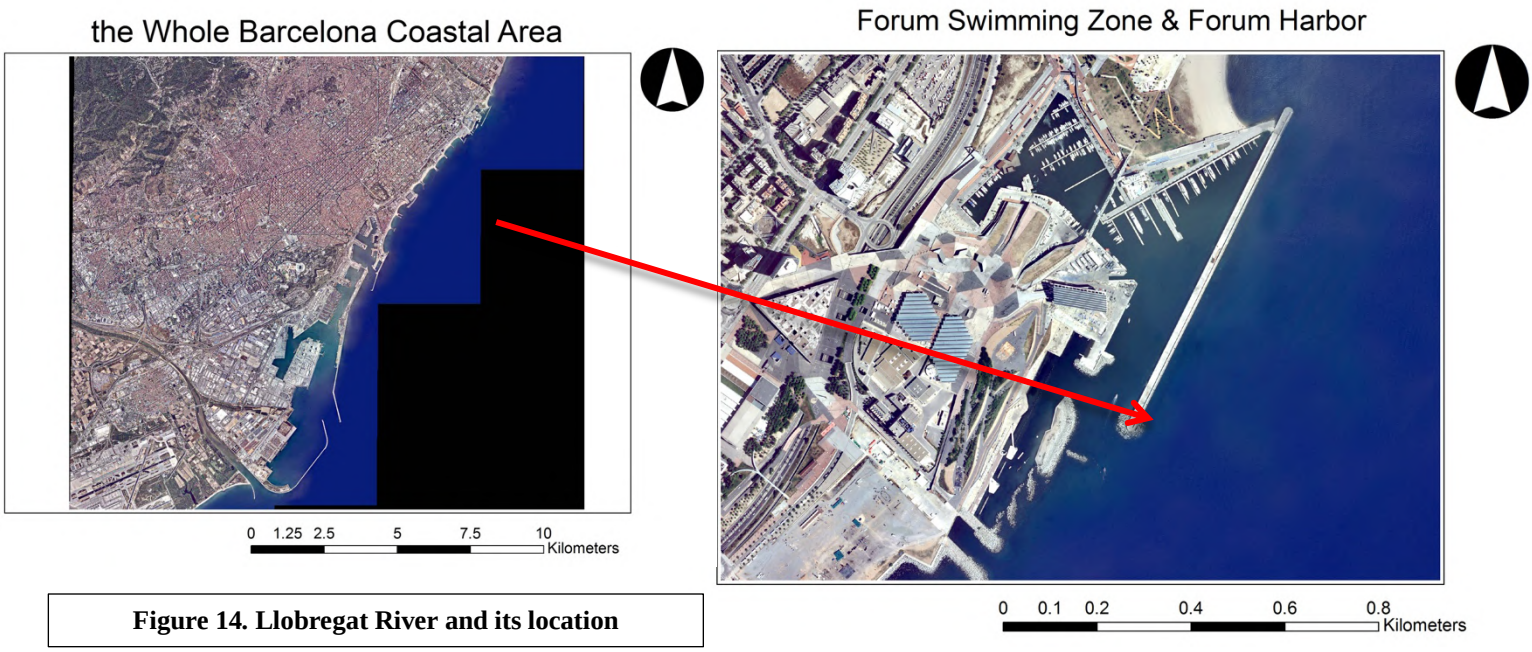

Figure 14. Llobregat River and its location

Fòrum Swimming Zone & Fòrum Harbor, including the swimming zone and the whole Fòrum Harbor;

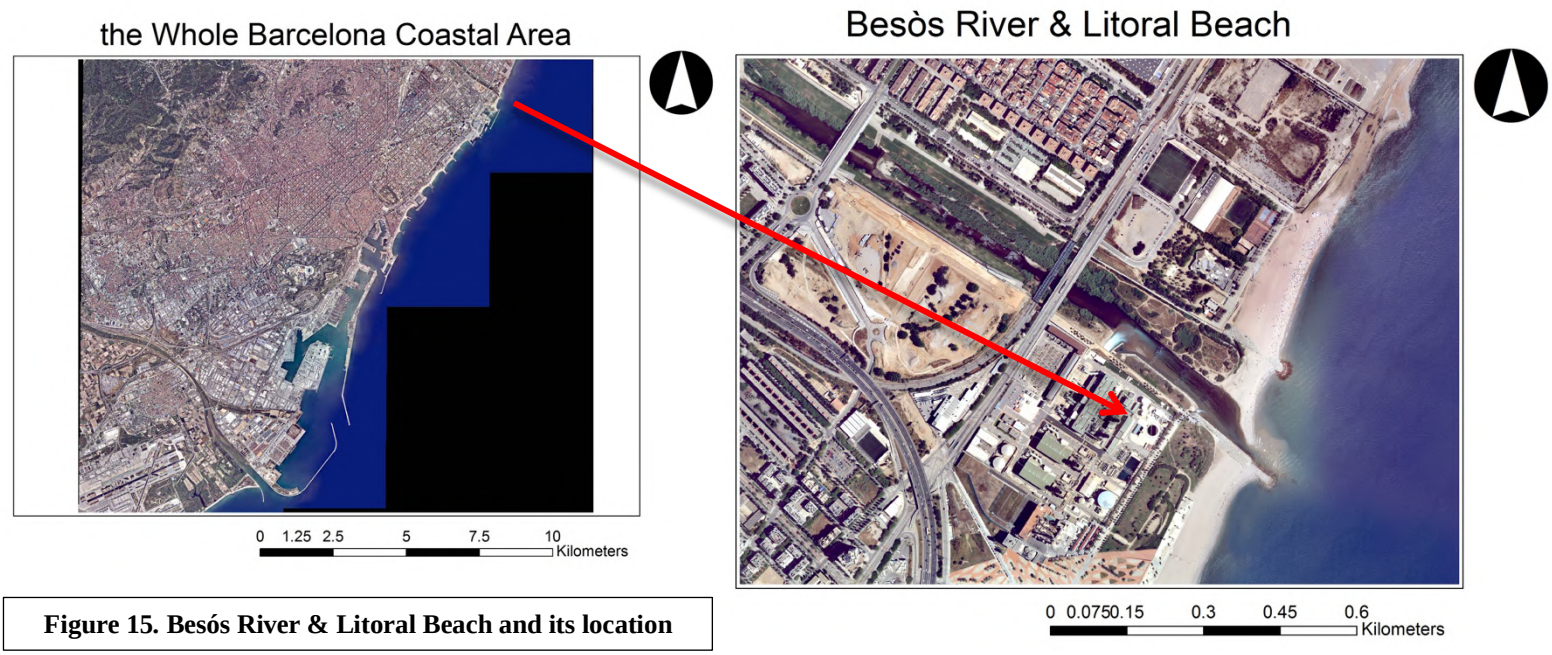

Figure 15. Besós River & Litoral Beach and its location

Besós River & Litoral Beach, including both banks of Besós river and Litoral beach, which located on the left bank of Besós river estuary.

Sea Level Rise projection in future scenario

50% scenario

In this scenario, the influence produced only by sea level rise. According to projection in medium level, the sea level rise will increase for 0.05 m. The orange polygons in following images show the impacts on Barcelona coastal area after sea level rising 0.05 cm in 2100 projection. Under this projection, the whole coastal area is quite safe, there is no influence in the whole area instead of in Front Harbor.

As the picture showing, the only influence appears in this scenario is the repairing dock in Front Harbor. Considering the function of this place, which is to fix or preparing the ships. Hence, the flood situation also depends on whether there is ship inside or not. The water height would increase if there is a ship located inside, otherwise, the threaten of this spot is not serious.

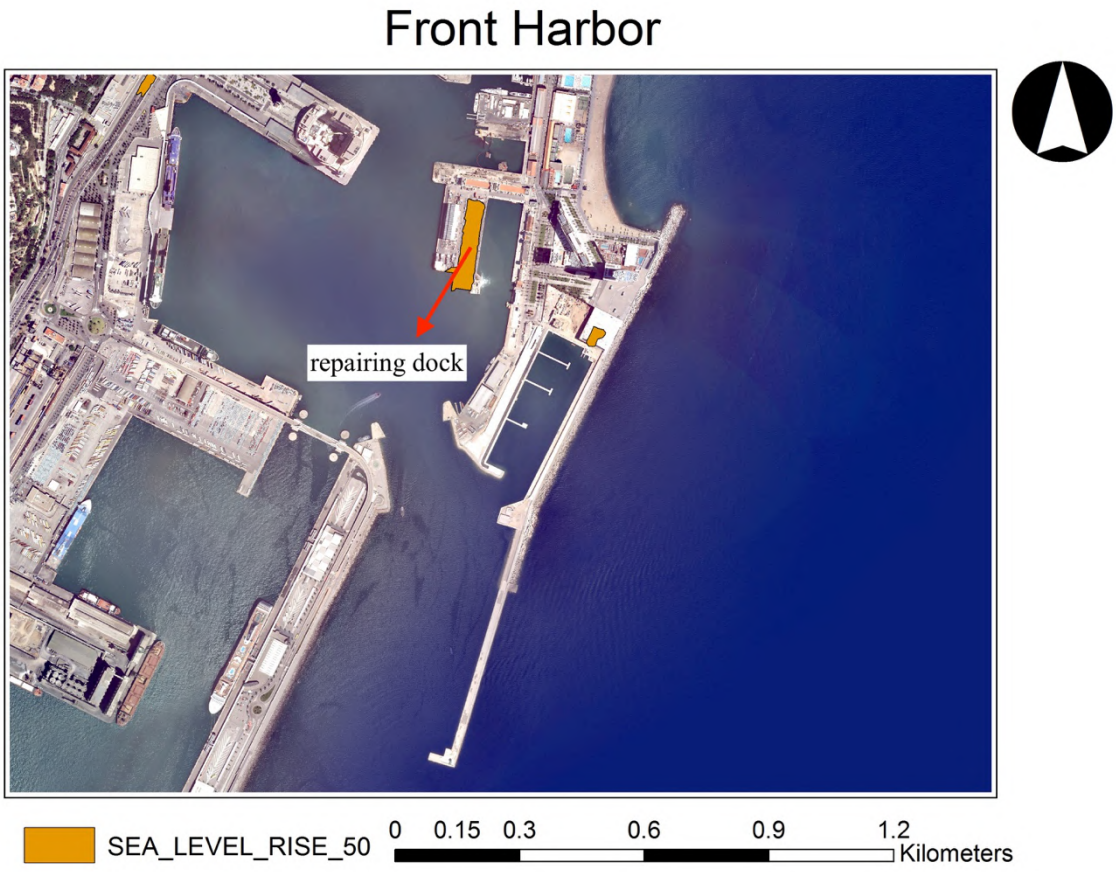

Figure 16. 50% SLR projection at Front Harbor

90% scenario

In this scenario, the influence produced only by sea level rise as well, the sea level will rise up 0.32 m compare to current scenario. There are 9 parts of Barcelona coastal area will be flooded in different severe levels. The red color polygons show the influences after water level rising 0.32 m:

Llobregat River Estuary

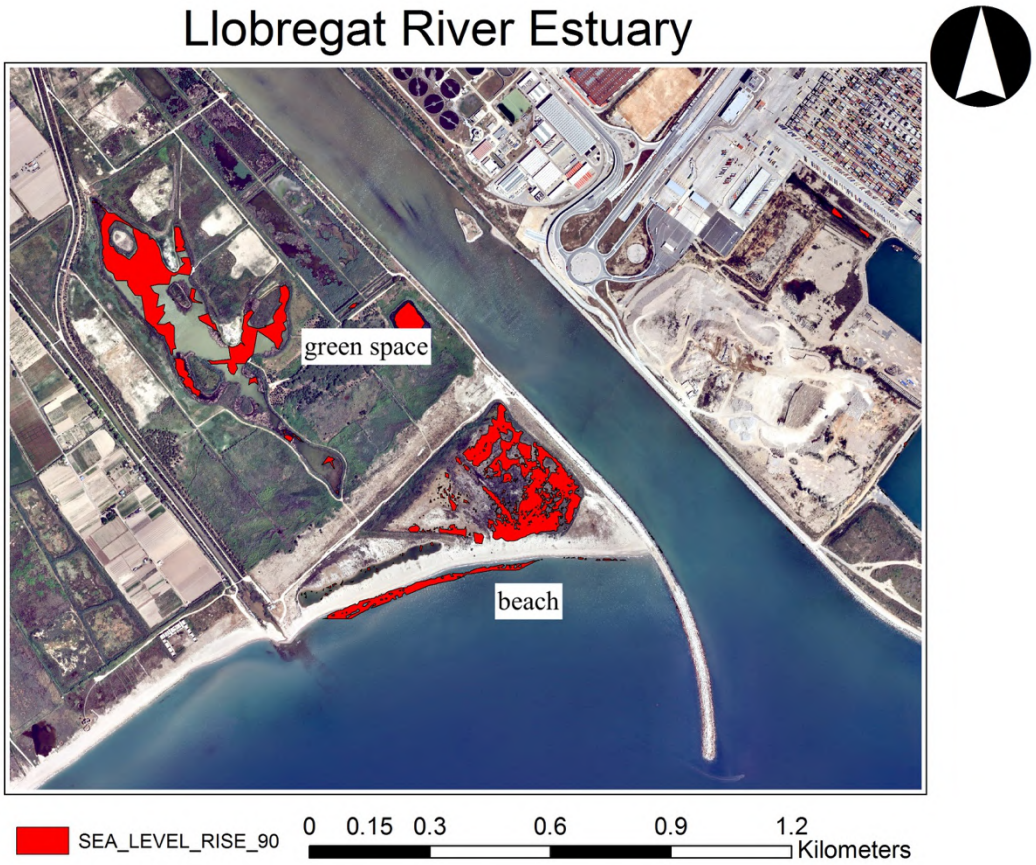

Figure 17. 90% SLR projection at Llobregat river estuary

In Llobregat River Estuary, firstly, some parts of green land would be flooded. Because of the influence parts do not direct link to the sea, it can be assumed that the flooding caused by the groundwater table rise. Due to the sea level rise, it would lead to the impact on ground water table height at the same time. The problem is, even if just small increase on ground water table, the risk of salt water invades into inland is an environmental threaten, especially in the part next to the sea. In some shallow inland, such as the nature pond in this picture, is able to easily get flooded. Secondly, the beach there will get influence as well. The beach

next to Llobregat river estuary would be flooded around 20 meters on average. Even though, it is not a famous beach in Barcelona, it has risk to be vanished in someday if there is no adaptation method to avoiding sea level rise.

Llobregat river

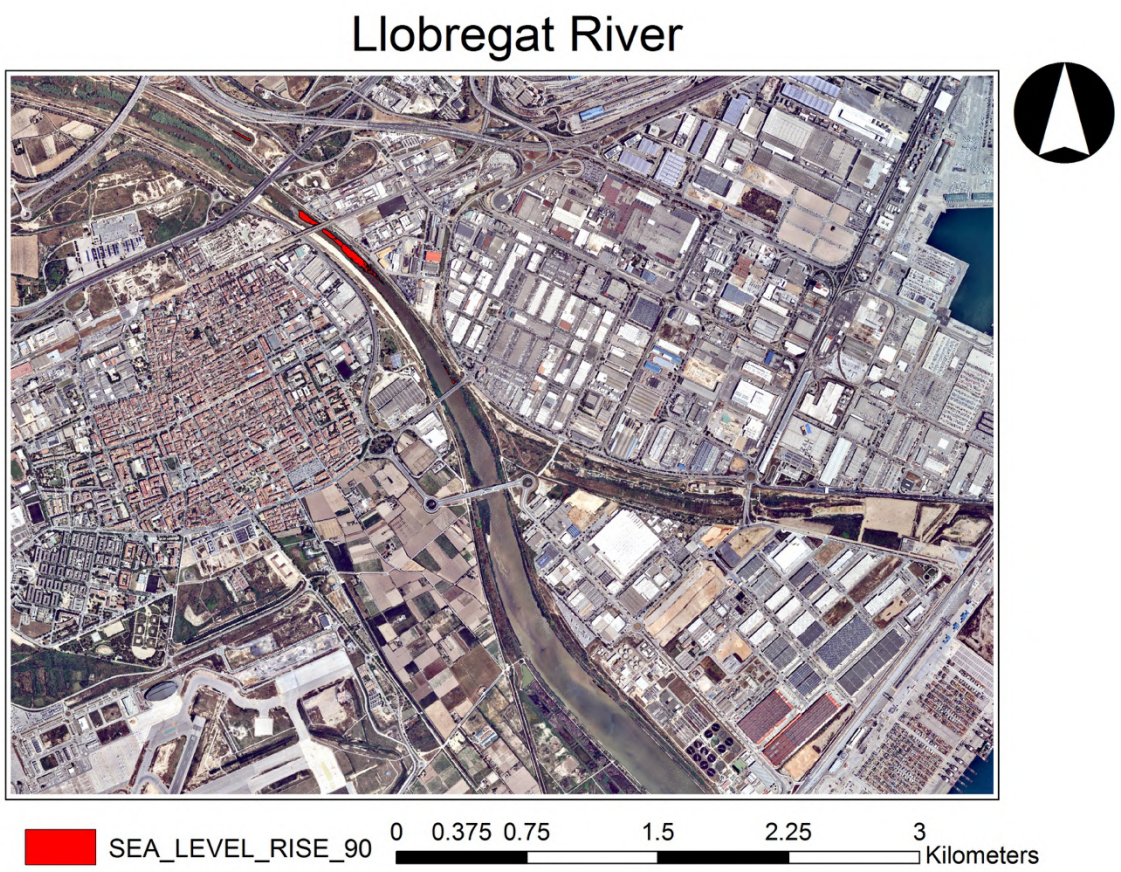

Figure 18. 90% SLR projection at Llobregat river

In Llobregat river, the vulnerable place is left river bank. However, the impacts are not as severe as showing in the picture. Actually, the red part is almost located in the river, where is all covered by water in current scenario. Hence, the biggest threaten is not the flood direct produced by sea level rise, it could be the river downstream boundary condition change due to the sea level rise. The changes can lead to different hydraulic performance in the Llobregat river, in some chances, the river flood would increase or the be more extreme. The same as above situation, another problem is the changes of the biological environment in downstream part since the much saltier water invade in river.

Oil Harbor

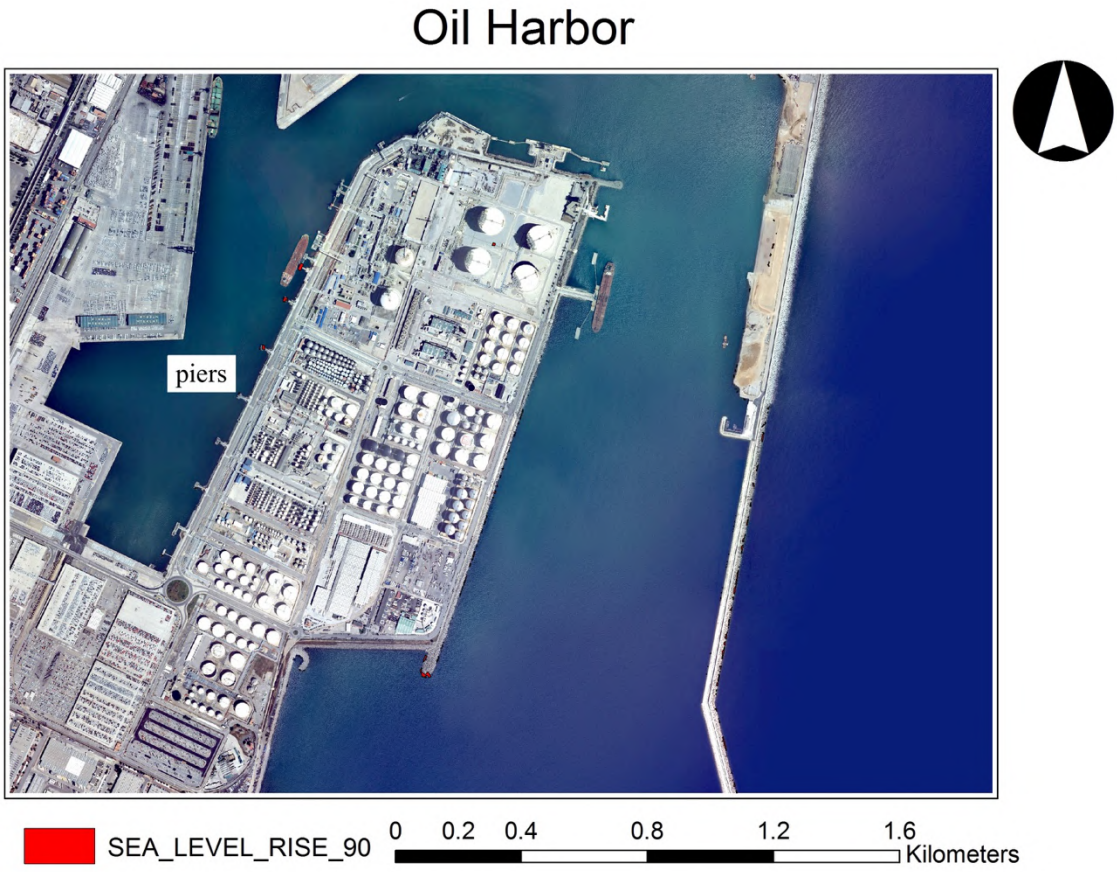

Figure 19. 90% SLR projection at oil harbor

In Oil Harbor, the influence focuses on piers. There are four piers can be flooded due to the sea level rise, three of them are almost fully flooded.

Front Harbor

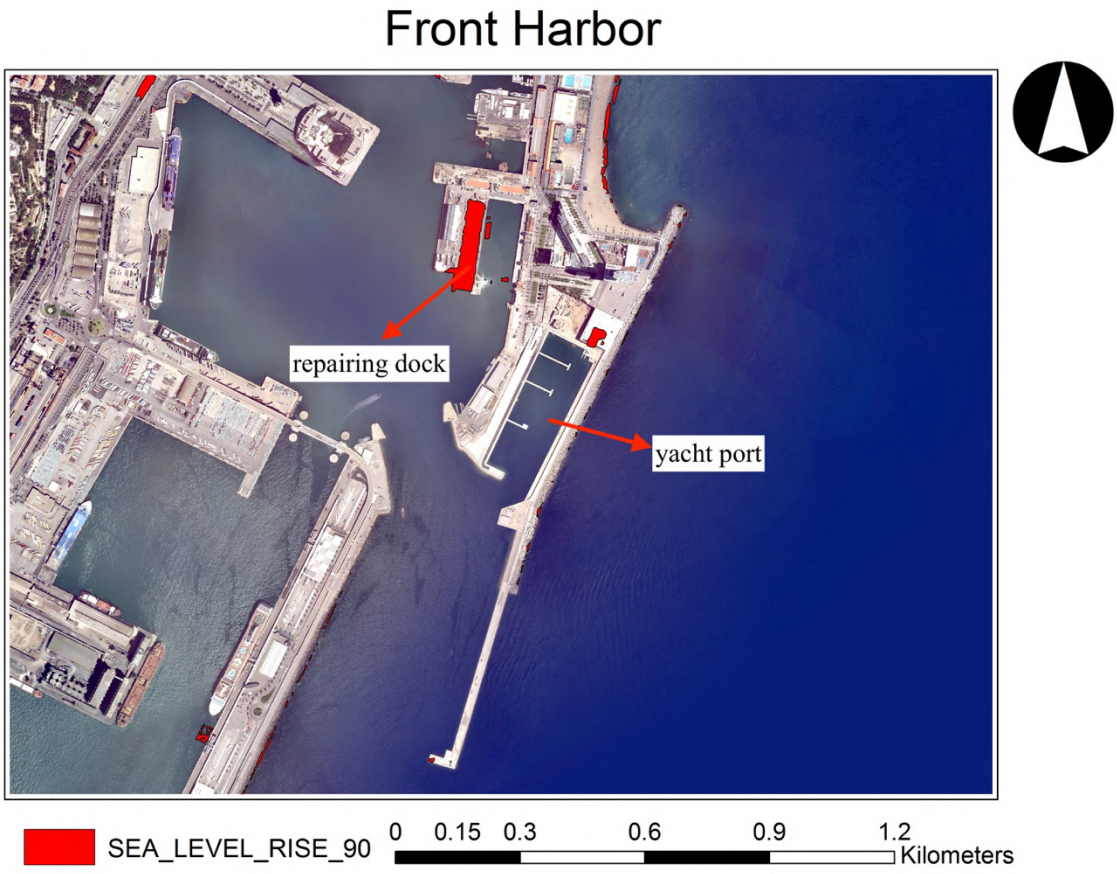

Figure 20. 90% SLR projection at front harbor

As the same as the previous scenario, the vulnerable place is on repairing dock, and the flood situation depends on its working status. And the results show a little influence on the north quay in the yacht port, however, according to field trip to check the elevation, the flooding cannot reach to the quay in this scenario (please check more details in the section “correction based on the reality).

Barcelona Harbor

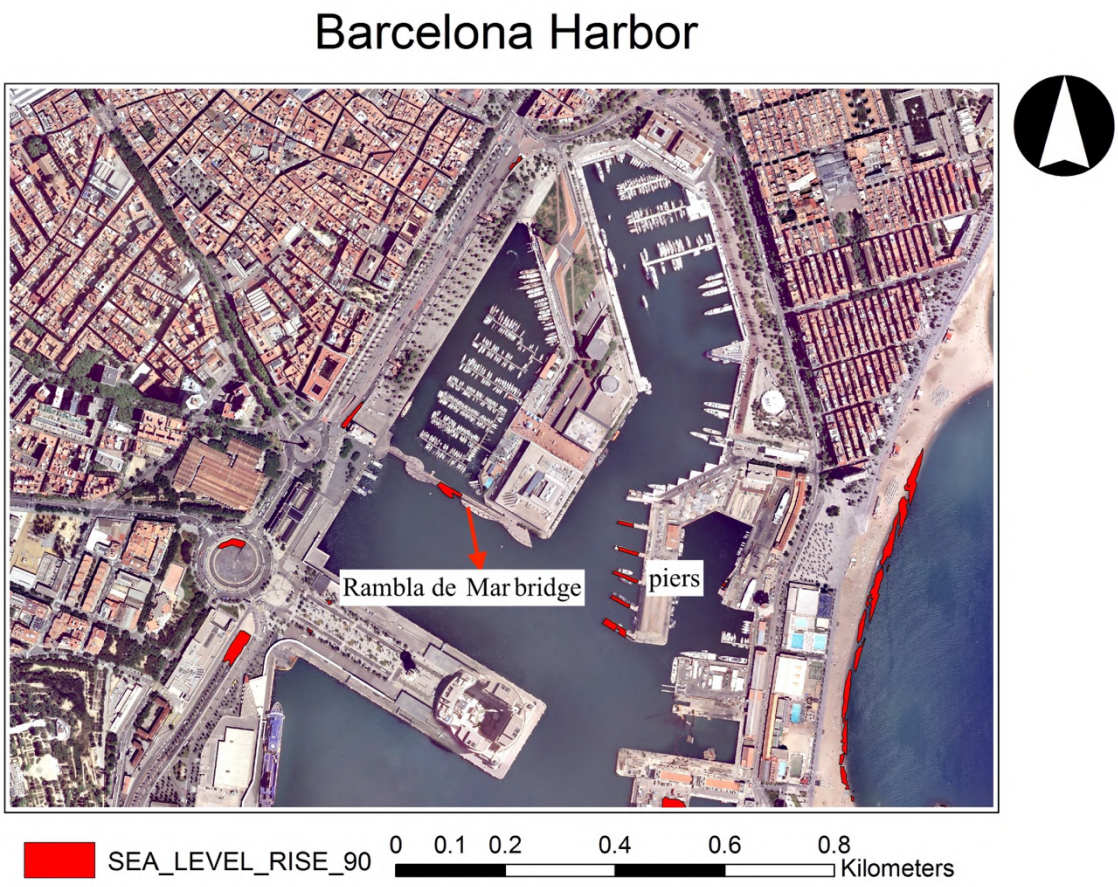

Figure 21. 90% SLR projection at Barcelona harbor

In Barcelona Harbor, according to the projection, there are three main parts would get influence due to the sea level rise.

First one is the tourist bridge named Rambla de Mar, it was designed as multilevel. In the results map, it shows that the first layer would be influenced by the water. However, according to the field trip for verifying DEM, the height from water surface to the bottom of bridge in current scenario is much larger than 32 cm (for more details, please check the section “correction based on reality”). The second part is five piers, they all would be fully flooded. And the last part is repairing dock, as the mentioned above, the flooding situation here depends on whether it under working or not.

Barceloneta Beach group

Figure 22. 90% SLR projection at Barceloneta beach group

In Barceloneta Beach, three different parts of beaches have different level of risk being flooded.

On the first one located at the south-west, the average flooding width is around 17 meters, the middle one is around 10 meters and the last one is around 15 meters. And the breakwater between them will be flooded in this scenario.

Olympic Harbor

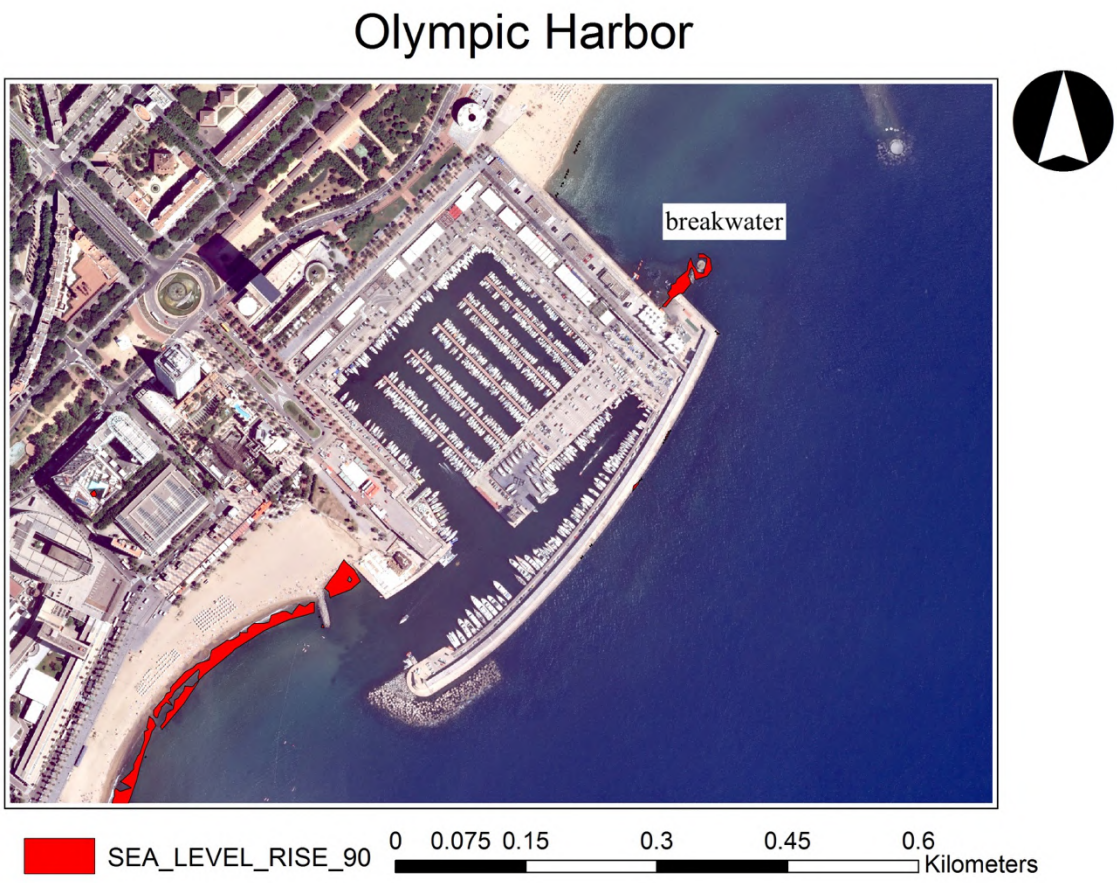

Figure 23. 90% SLR projection at Llobregat river estuary

In Olympic Harbor, there is no significant influence instead of one breakwater located at the north-east of harbor.

Figure 24. 90% SLR projection at Llobregat river estuary

In Llevant Beach & Océanos Buceo Profesional, three beaches all would get influence. The most severe part is the middle part of beaches, where around 25 meters width of beach would disappear in this scenario. Other two parts beaches can get influence around 4 and 6 meters respectively. The breakwaters on north-east can get little influence and it does not impact on the function of breakwaters, it still can block water from sea to protect the platform.

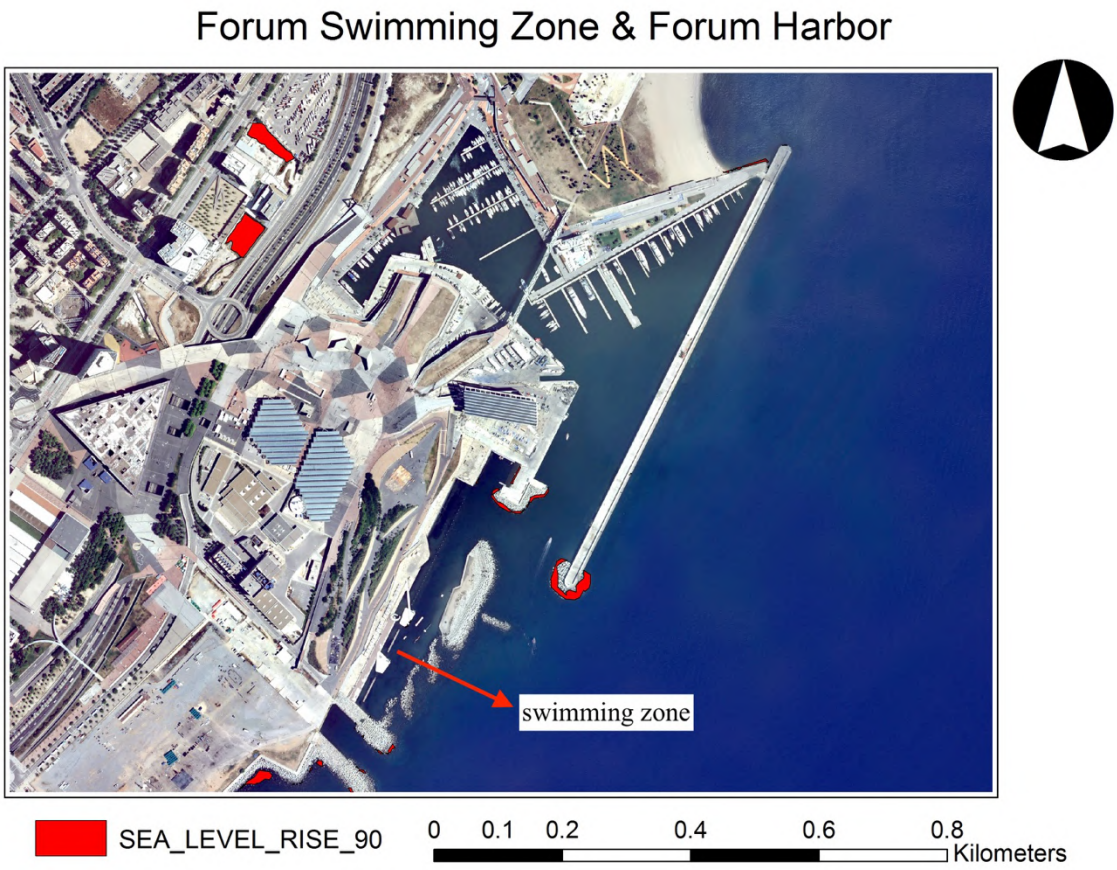

Figure 25. 90% SLR projection at Llobregat river estuary

In Fòrum Swimming Zone & Fòrum Harbor, the swimming zone would get no influence, and the whole Fòrum harbor is quite safe in this scenario. Only one part of breakwaters on the jetty can get influence and it does not affect the normal function of harbor.

besós river & Litoral beach

Figure 26. 90% SLR projection at Besós river & Litoral beach

In this area, only the breakwater gets some small influences. Besides this, the invisible impacts on river, such as the salty water flow into river would change the ecosystem, the downstream boundary condition would change due to the sea level rise need to do more simulation and test to be clarify.

Summary

Under 90% sea level rise projection, most parts just have small influence could not cause big damage. The most vulnerable places are five docks in Front Harbor, Barceloneta Beach and Llevant Beaches. Comparing 90% sea level rise projection, the influence in 50% projection is close to zero. There is only one part can get impact in this scenario: the repairing dock in Front Harbor, and it also depends on its status whether it is under working or not. Generally, it seems the whole coastal area in Barcelona is quite safe if only considering sea level rise projection. Without doubt, even if it is a small influence, there still can cause damages in different aspects. For instance, on the beaches, if there is no useful approach stopping sea water, the tourism on these beaches would get influences and lead to impact on economic losses.

The influence on different area shows in following table: if the influence is big enough to affect the components not being able to use anymore, the fonts is in red; if there is influence but can still operate properly, the fonts is in black; if there is a blank means there is no influence in that return period. (all the influences are based on result map corrected by field trip)

Table 2. Influence results in 90& Sea Level Rise projection

90% SLR projection	**Estuary of Llobregat river**	beach
		green area
		breakwater
	Oil Harbor	4 piers
		2 piers
	Front harbor	repairing dock*
	Barcelona Harbor	5 piers
		repairing docks*
	Barceloneta beach group	beach
		middle breakwater
	Olympic Harbor	breakwater
	Llevant beach& Océanos Buceo Profesional	breakwaters
		beach
	Fòrum swimming zone & Fòrum harbor	breakwater
	besós river & Litoral beach	breakwaters

*Note: 1. * means its flooding situation depends on its status. 2. Influence in black and damages in red.

Current Sea Level + Storm Surge

Under this scenario, the yellow, red, blue, green and purple polygons in following figures show the impact of T1, T10, T50, T100 and T500 storm surge respectively on the coastal area of Barcelona in the current sea level scenario. The table shows the height of different time return period storm surge in current scenario, which means during different return period storm surge, how much will increase on sea level. Under this scenario, there are 12 parts in Barcelona coastal area can be flooded (the container harbor will not have influence), each of them has different risk level.

Table 3. Water increase height in current scenario + storm surge projection

Storm Surge Return Period	Current Scenario (1986-2015)
T1	0.46 m
T10	0.67 m
T50	0.87 m
T100	0.97 m
T500	1.24 m

Due to there are same influence part in different return periods in the same location, the analysis description following will be divided into areas, that is, the all different return periods storm surge is overlapping into one location map and the analysis on these storm surge will describe together.

Llobregat River Estuary

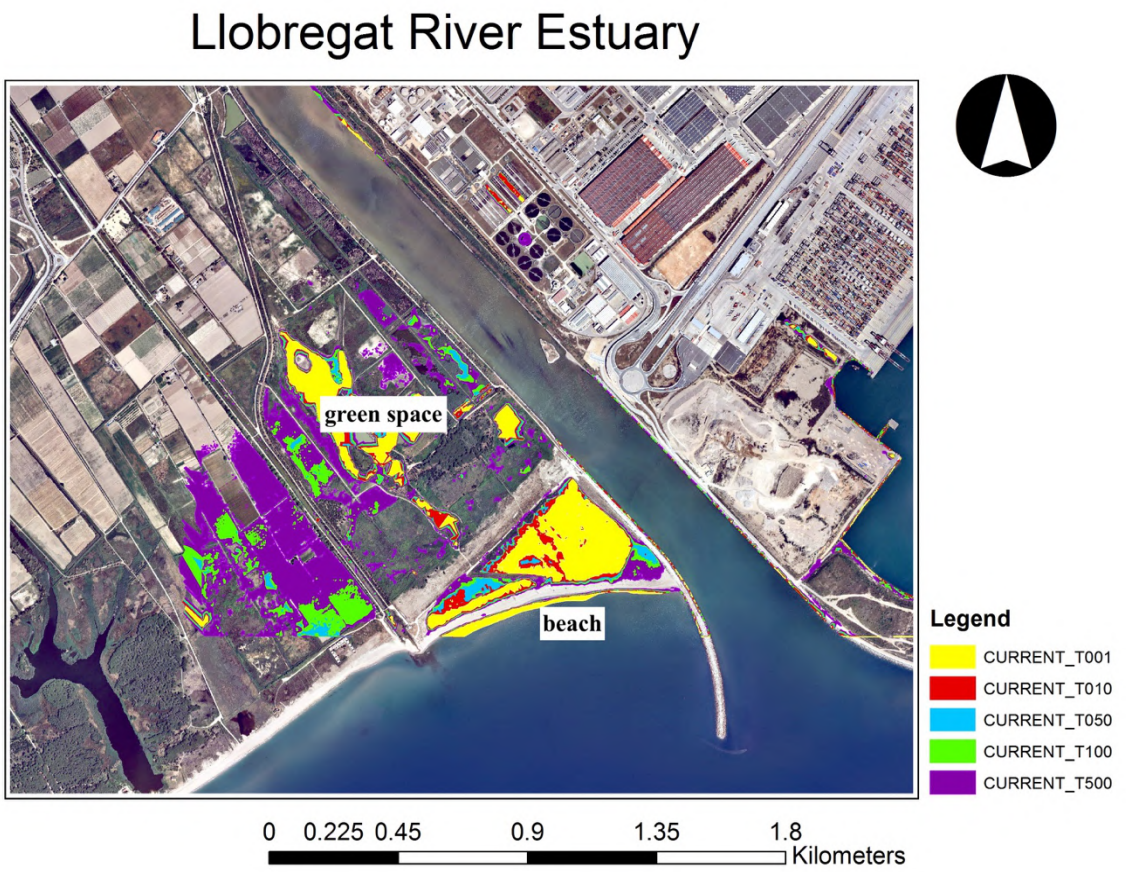

Figure 27. Current scenario + Storm Surge projection at Llobregat river estuary

In Llobregat river estuary, the most vulnerable places are beach, green land and breakwaters. The beach and breakwaters will get influence direct from sea starting from T1 storm surge. The beach will be pushed back on average around 15 to 20 meters during different storm surges. There are also some influences on breakwaters, however, the water cannot cross it enter interior, it still can protect river banks perfectly. Even if the sea water cannot jump over breakwaters or beaches to reach to green land, due to the low elevation, the green space can be influenced by the ground water. The sea water invades into ground water and arise up the ground water table, the low-lying area will get easily flooded. As it shows in the picture, in current scenario with T1 storm surge, which can increase current sea level 0.46 meters, is already high enough to cause damage on beach and green space. It can shrink the width of beach and the green land area, even destroy the biologic environment in green land due to the salty water. And some influences on breakwaters cannot impact its function, so the river bank can be perfectly protected.

Llobregat River

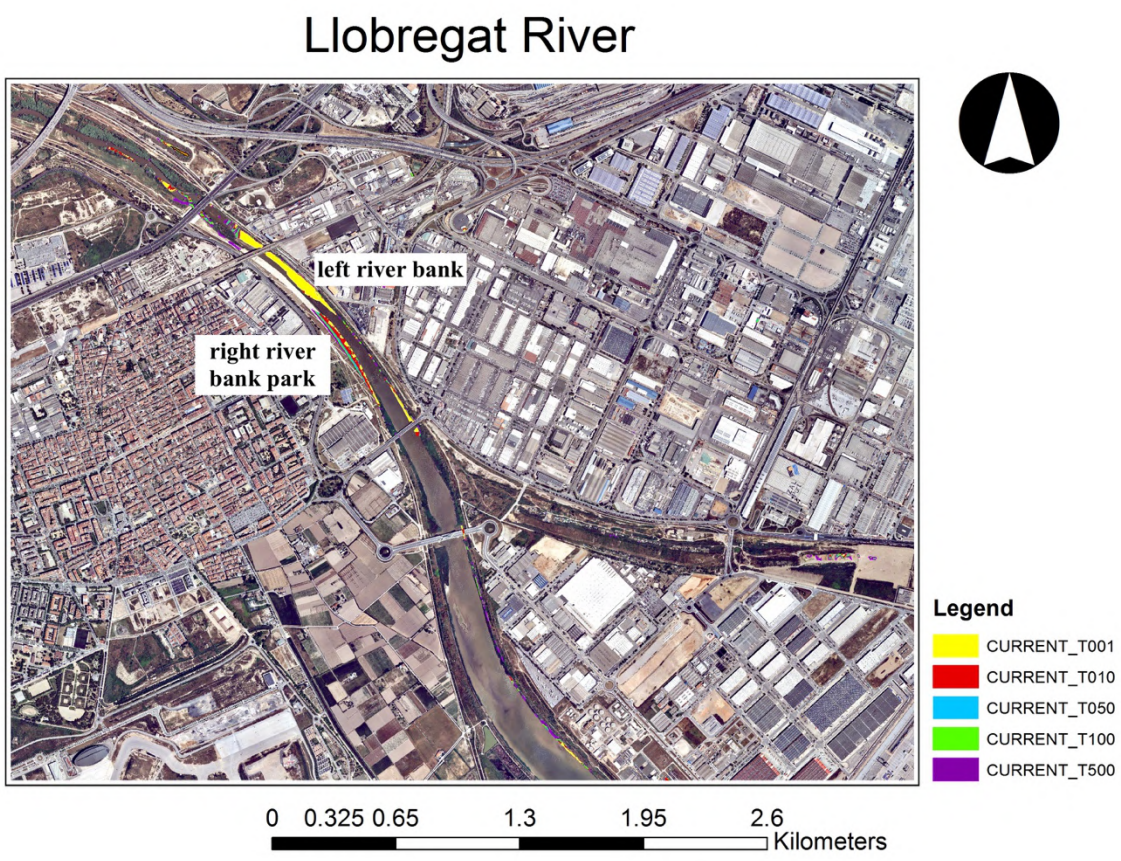

Figure 28. Current scenario + Storm Surge projection at Llobregat river

In Llobregat river, the vulnerable part is focusing on right bank. There is a park on the right bank for citizen walking or jogging, and it can be flooded starting from T1 storm surge. Through sea level rise caused by storm surge, sea water can invade river from estuary and increase the river table. On the one hand, the both river banks can get influence directly; on the other hand, the new sea level will change the downstream boundary condition of the Llobregat river, which can lead to a change of the whole river hydraulic dynamic performance, increasing the risk in extreme events. What's more, the salty water enter into the river can change the biology environment, this would be a great threaten to the river ecosystem.

On the left river bank, it also shows the impact polygons, however, due to the impact parts are located inside the river, a reasonable assumption is that the digital elevation model here shows the plants in the river instead of any structures. Hence the impact on the left bank

cannot cause big influence, the left bank can protect left part continuously. Instead, the paths in river bank are in the most serious situation that can be flooded around a width of 38 meters, it has a risk at citizens' normal activities or even life safety. Hence, during the storm surge, it is necessary to issue a hazard warning.

Figure 29. Satellite image of Llobregat river right bank park

Llobregat River Left Bank Harbor

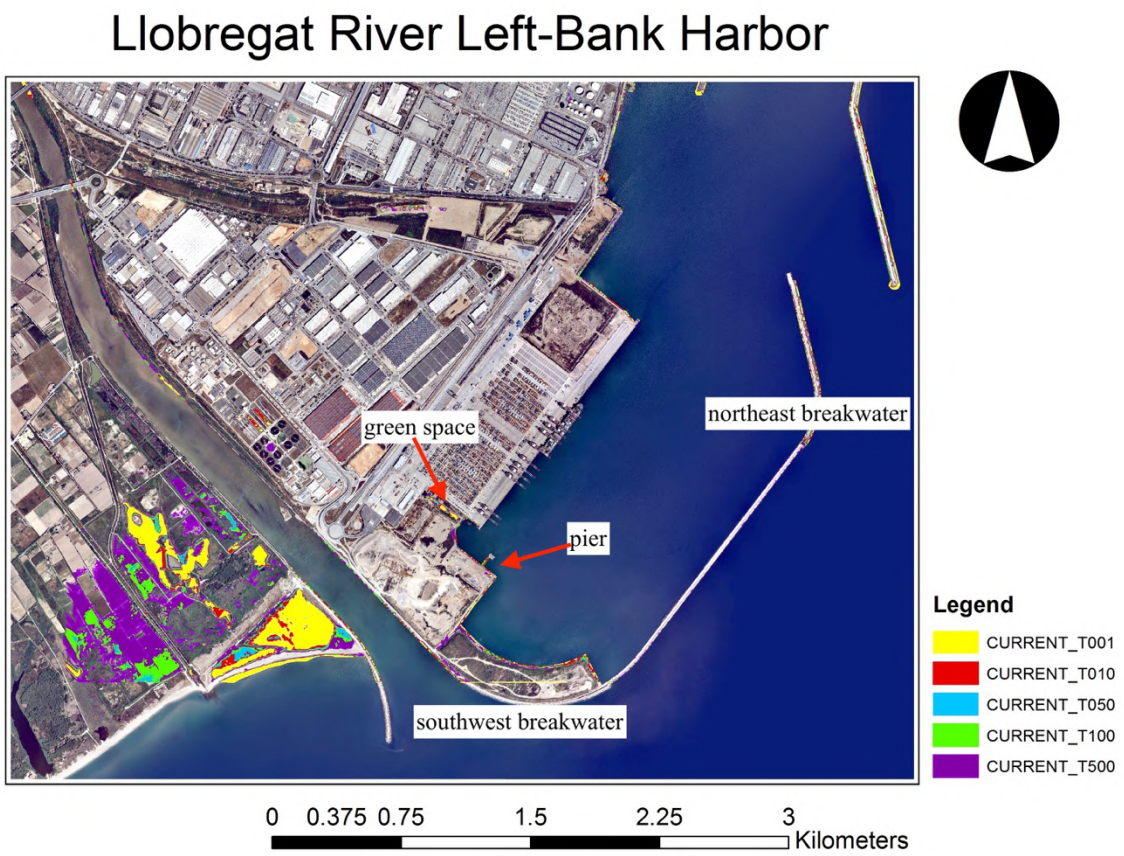

Figure 30. Current scenario + Storm Surge projection at Llobregat river left-bank harbor

In Llobregat river left bank harbor, the influences on breakwaters, small space and green space are notable. The breakwaters located in south-west and north-east are vulnerable, they can always protect inside properly until encounter the T500 storm surge. During T500 storm surge, the water will cross the breakwaters and enter into the harbor. The small pier on the left will start getting influence during T10 storm surge and totally flooded during T500 storm surge. The green space next to the quay will be totally flooded starting from T10 storm surge. According to the satellite image, the green space is a no-functioning place for now, but it could be used for any operation in the future, so it also needs be take care of its low elevation condition. Besides the influences mentioned above, the breakwater along the sea is more or less impacted by storm surge, but it cannot cause any serious damages.

Oil Harbor

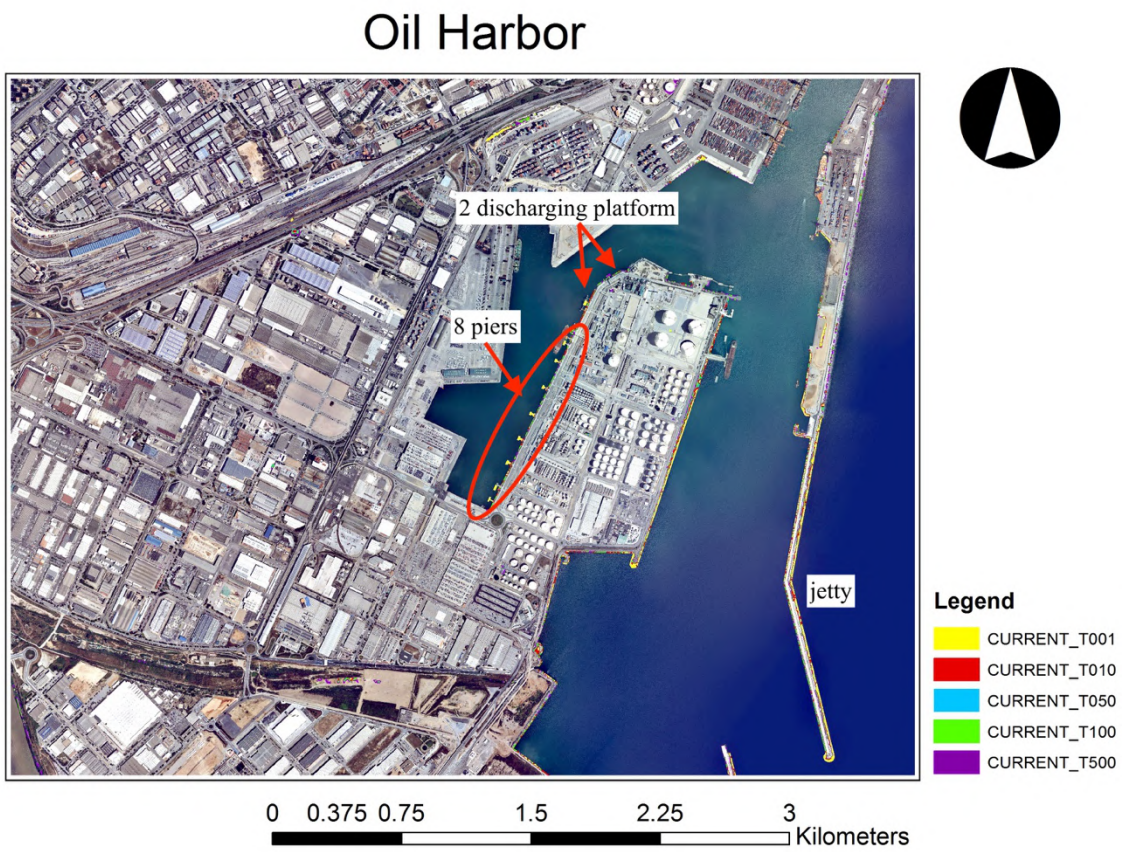

Figure 31. Current scenario + Storm Surge projection at oil harbor

In the oil harbor, the piers and discharging platforms along the quay are easily getting flooded. There are 8 docks located on the west of harbor will be flooded starting from T1 storm surge, 2 discharging platforms located on the north-west will be flooded starting from T50 and T500 storm surge respectively. The jetty surrounding this harbor can continuing protect harbor well since the storm surge is not able to cross the it.

Front Harbor

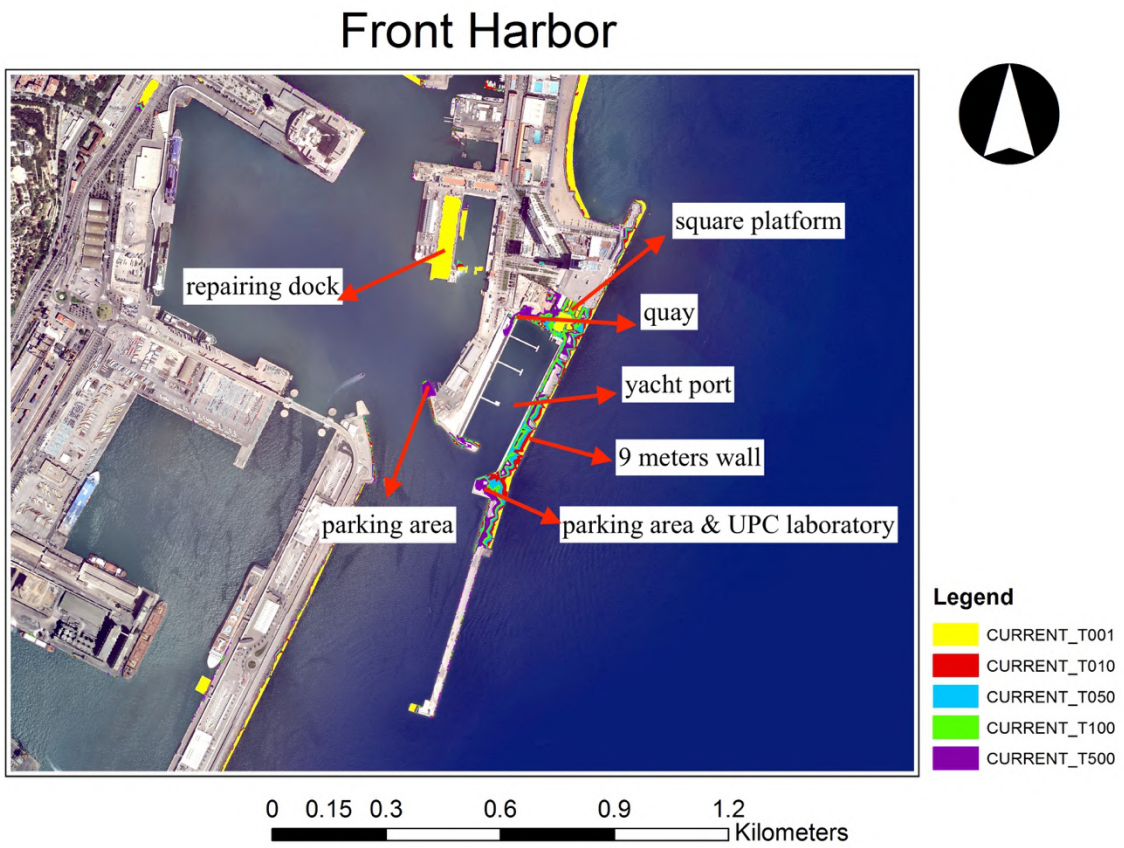

Figure 32. Current scenario + Storm Surge projection at Front harbor

Front harbor is a vulnerable place, the repairing dock, quay, breakwaters and parking area all can get influences by storm surge. The repairing dock, as previous scenarios, the flooding situation depends on its working status, if the ship parking inside, it would have a big risk to get flooded. The quay located on the north corner of the yacht port will be flooded during T500 storm surge. Two parking areas, one of them only for parking and another one has a UPC laboratory as well as parking area, will be flooded starting from T10 storm surge according to the results map.

Additionally, there are some places will be flooded even if they are not showing in the map. The problem caused these differences is the digital elevation model is too old or it has some errors. Three piers inside yacht port, according to the result shows in the map, there is no influence polygons. However, after checking through the field trip, the piers inside are fixed,

they cannot float with the water increasing. The height of piers is around 0.8 meters, which means the piers will be flooded starting from T50 storm surge.

On the contrary, some places are not able to be flooded but there are influence polygons in the results map. For instance, the results map shows a severe flood on the north quay inside the yacht port. However, according to the measurement, the height of quay on the north part is around 1.5 meters, and the square platform right behind the quay is already constructed a three-floor building used as garages or restaurants. Obviously, the digital elevation model of this area need update. As the same as the quay, the breakwaters on the east cannot be flooded as well because there already built a nine-meter wall to block sea water.

Figure 33. Three-floor building located on the north of quay in the yacht port

Figure 34. Nine-meter wall along the sea

Figure 35. Fixed pier in the yacht port

Barcelona Harbor

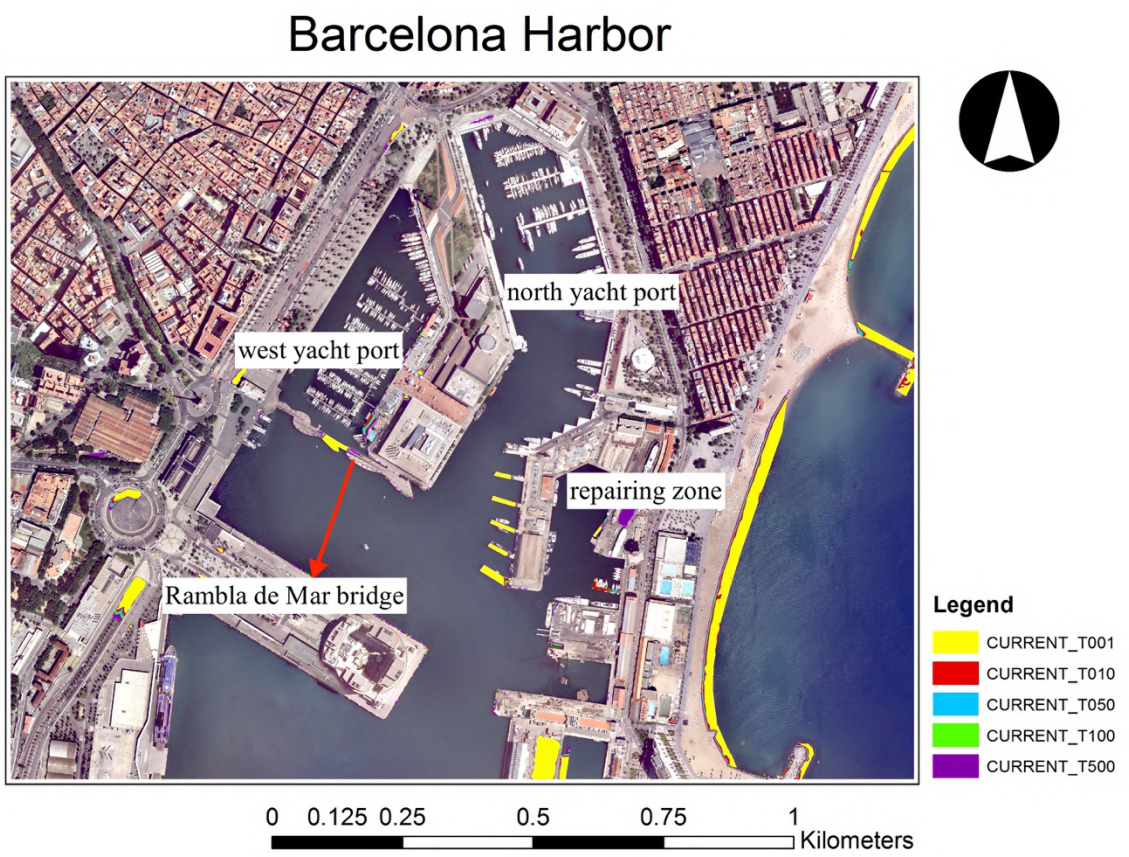

Figure 36. Current scenario + Storm Surge projection at Barcelona

In Barcelona harbor, the vulnerable places are focusing on yacht port located on the west and the repairing zone located on the east. The 7 piers in the repairing zone will get flooded starting from T1 storm surge. Besides that, the docks inside the repairing zone also can easily get flooded depending on their working status. The quay inside west yacht port will be flooded starting from T10 storm surge.

Additionally, the impact on tourist bridge named Rambla de Mar is not accurate. According to the measurement during the field trip, there are at least 1.5 meters between the bottom of the bridge and the water surface. In this scenario, the most significant storm surge can increase water height for 1.24 meters, but it still cannot reach to the bridge. Hence, there should be no impacts on Rambla de Mar bridge.

Barceloneta Beach Group

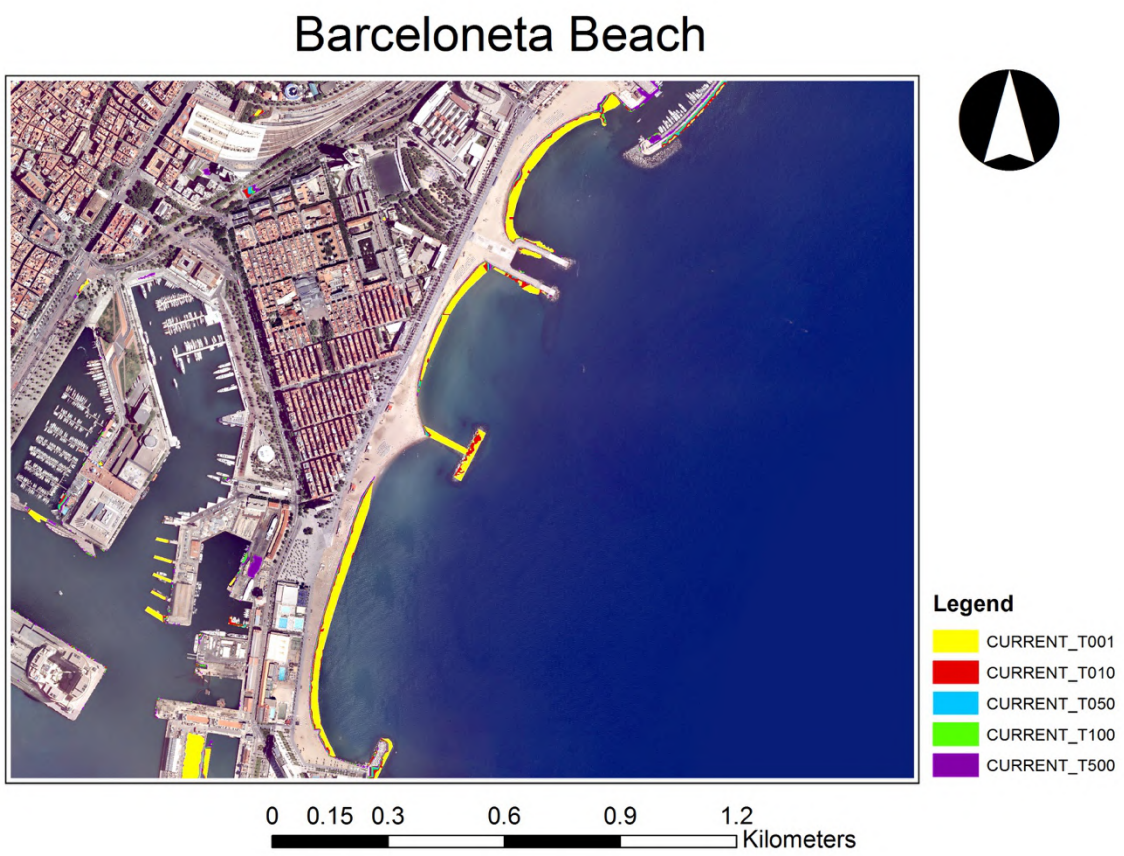

Figure 37. Current scenario + Storm Surge projection Barceloneta beach

This area separated into 3 parts geographically, they are all affected in different risk levels.

The first part of beach will decrease its width around 19 meters to 26 meters on average in T1 to T500 storm surge events; on the second part, the average disappear width is around 13 meters to 20 meters; the last one can get influence around 22 meters to 27 meters on average in different storm surge events. The two breakwaters separating beaches will be completely flooded starting from T1 and T10 storm surge respectively.

Olympic Harbor

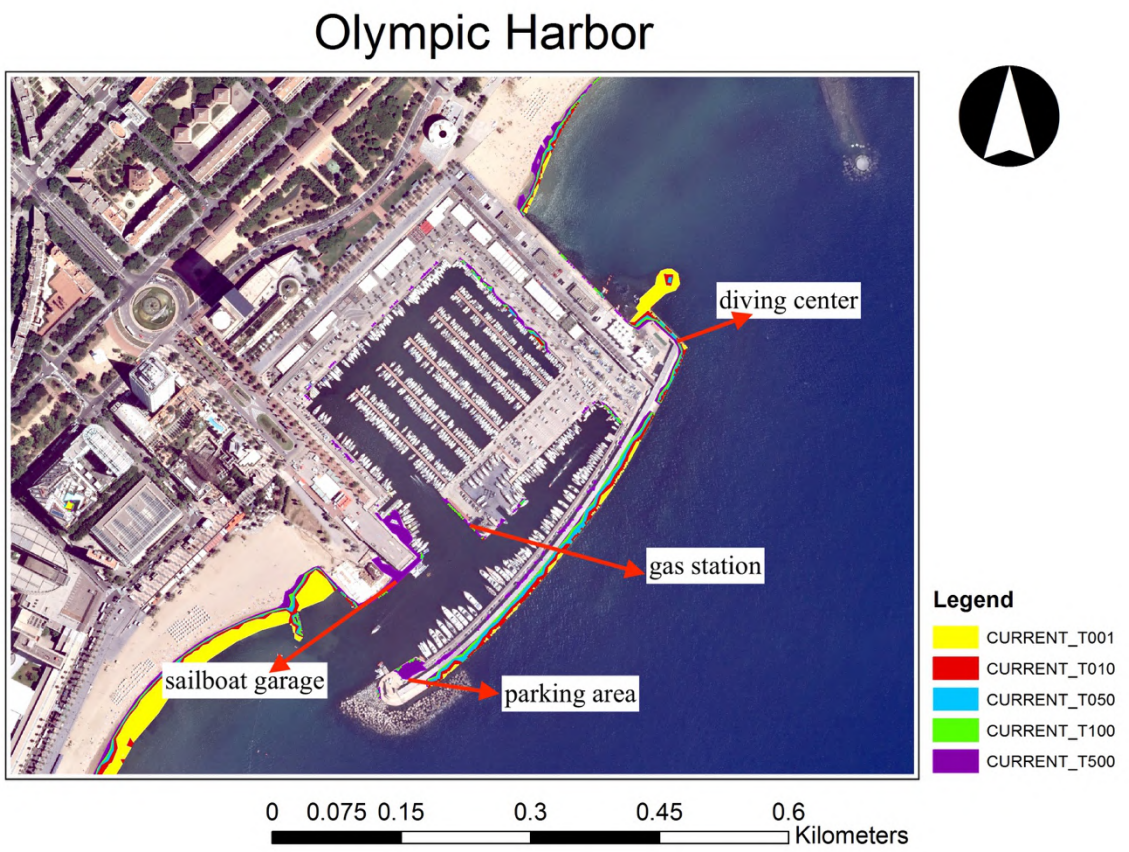

Figure 38. Current scenario + Storm Surge projection at Olympic harbor

The influences on Olympic harbor are quite complex. The quay, gas station, sailboat garage, parking area and breakwaters all can get different influences.

The elevation of quay located on the northeast is lower than other parts, thus, this area are easily getting influences. As the results map showing above, the northeast quay will be flooded starting from T50 storm surge. The gas station located inside the port is also vulnerable, it would be flooded starting from T100 storm surge. Because of its particular function, the flooding on this area is much riskier, it may cause the leaking problem or pollution in the sea. The sailboat garage located in the southwest corner can be flooded during T500 storm surge, and the restaurant located next to it can also get impacts. There is a small parking area located at the end of the quay on the southwest, it also can get flooded during T500 storm surge. About the breakwaters located on the northeast corner, the water will completely cover it during T500 storm surge.

At the same location as the breakwater, there is a diving center which including a slope extend into the sea for diving activities. Luckily, in this scenario, the sea water in each storm surges cannot reach to the diving center.

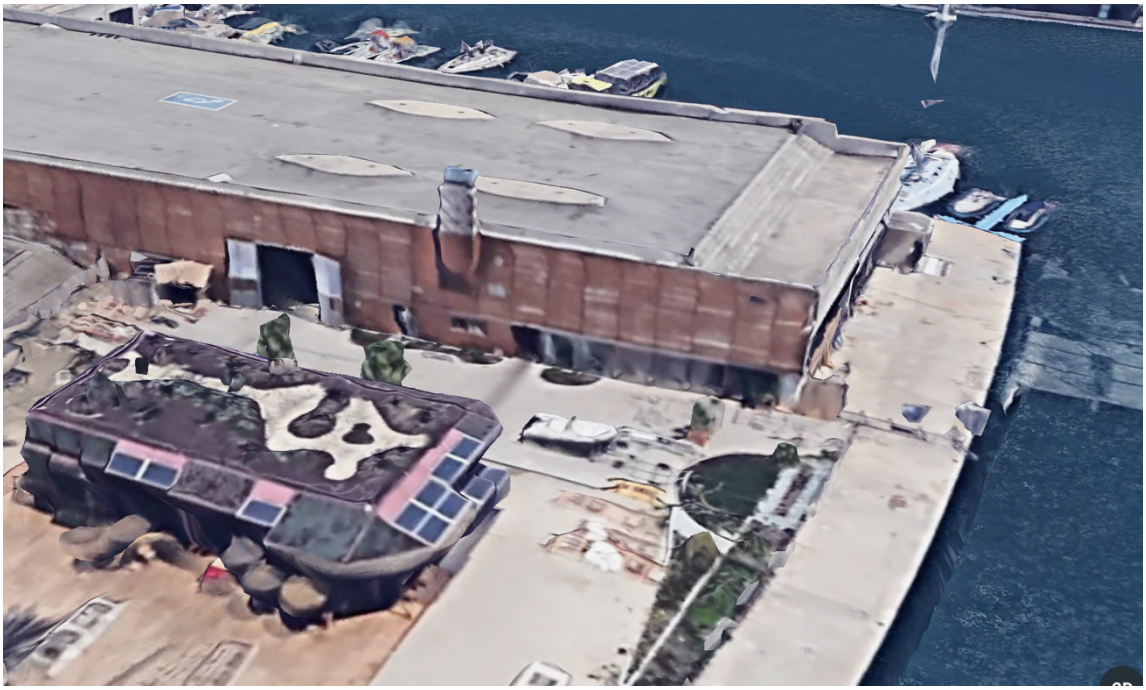

Figure 39. Sailboat garage and restaurant in Olympic harbor

Figure 40. Gas station in the Olympic harbor

Nova Lcaria Beach

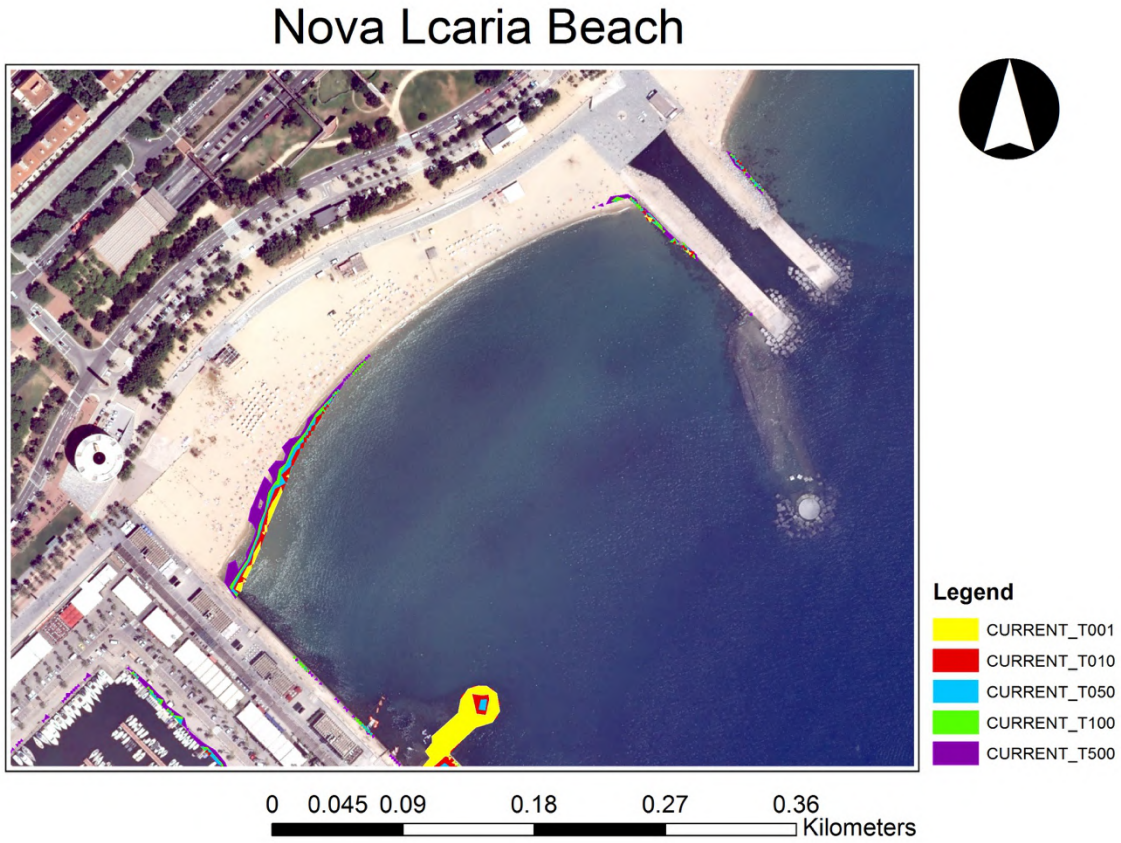

Figure 41. Current scenario + Storm Surge projection at Nova Lcaria beach

On this beach, only the west part will get influence, the maximum influence is around 15 meters.

Llevant Beach Group& Océanos Buceo Profesional

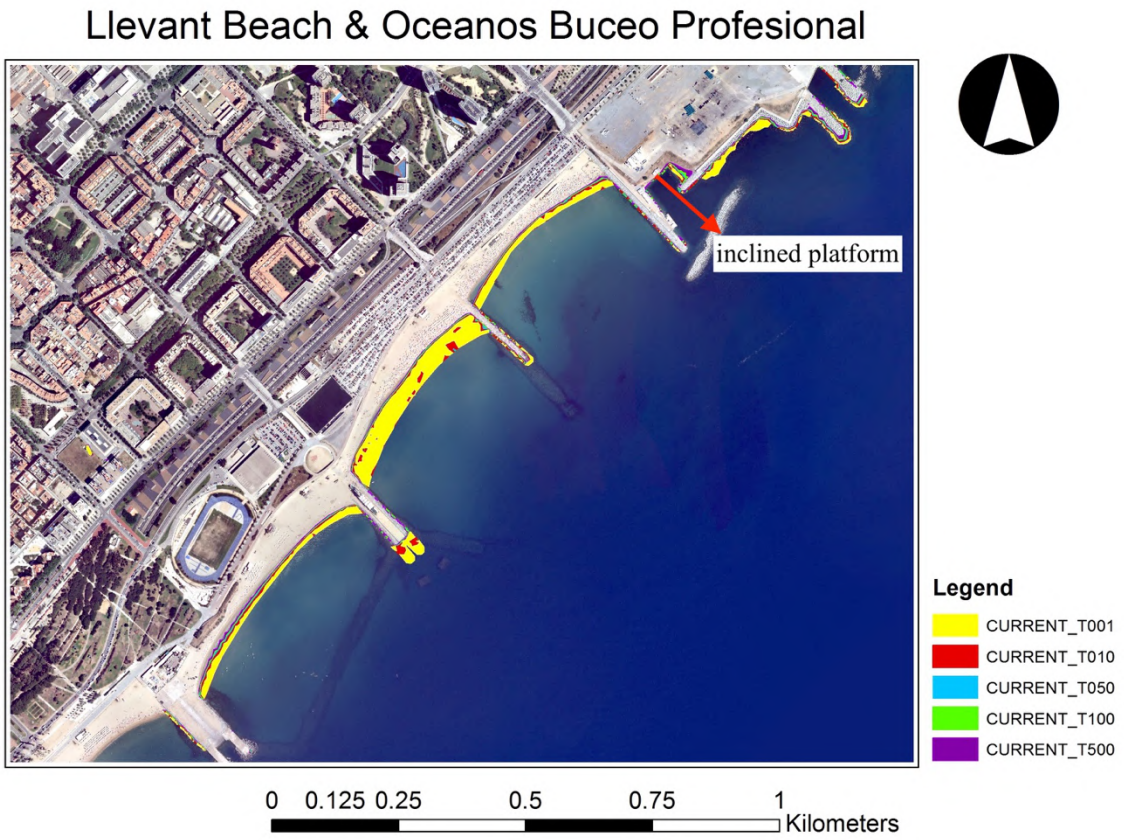

Figure 42. Current scenario + Storm Surge projection at Llevant beach group & Océanos buceo

There are three parts of beaches in this area, the first one can be flooded around 7 meters to 16 meter on average in different return period storm surges; the second part of beach is the most vulnerable part, the maximum influence on this beach can reach to around 40 meters on average in T500 storm surge; and the last part of beach can get influence about 6 meters to 10 meters on average during different storm surges. Besides these influences on the beaches, the influence on inclined platform is also notable. The width of sea water extending into interior can reach to 16 meters.

The breakwaters surrounding the professional ocean diving zone can continuing protecting inland properly, the maximum height storm surge is still not able to cross them.

Fòrum Swimming Zone & Fòrum Harbor

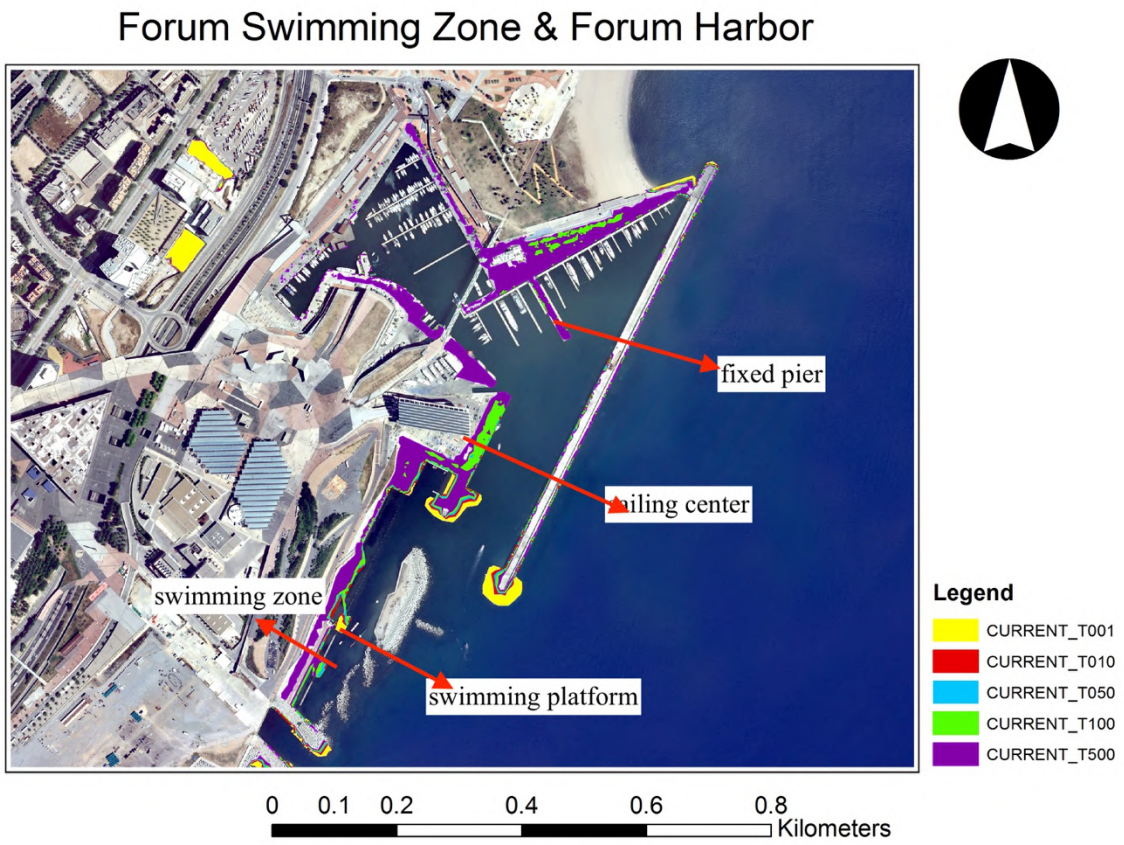

Figure 43. Current scenario + Storm Surge projection at Fòrum swimming zone & Fòrum harbor

This part also has a complicated situation, the swimming platform, quay, piers, roads and the international sailing center platform will be flooded.

In the swimming zone, the roads along the swimming area and two swimming platforms can get influences starting from T1 storm surge. During T500 storm surge, the platform will be totally flooded. The roads along the swimming area will have at least 20 meters width influence during the T500 storm surge, which can lead to a significant risk to citizens. Next to the swimming zone, the sailing center platform also can easily get covered by sea water. According to the results map, the whole platform surrounding international sailing center will be completely flooded starting from T100 storm surge. Through the field trip, this platform as far as we know is used for parking small sailboat. In the Fòrum harbor, all the piers are made by wood, which can float with the water increasing. Hence, the storm surge cannot cause influences on piers. However, one fixed pier and the quays are vulnerable, they will be

covered by water during T500 storm surge, and the water will continue flowing to the roads. Almost the whole Fòrum harbor will totally ruined if there is no adaptation to update.

The jetty leading to ship enter into the harbor is quite safe compare to other components, even if during T500 storm surge, the water cannot cross it.

Figure 44. One of the swimming platforms in the swimming zone

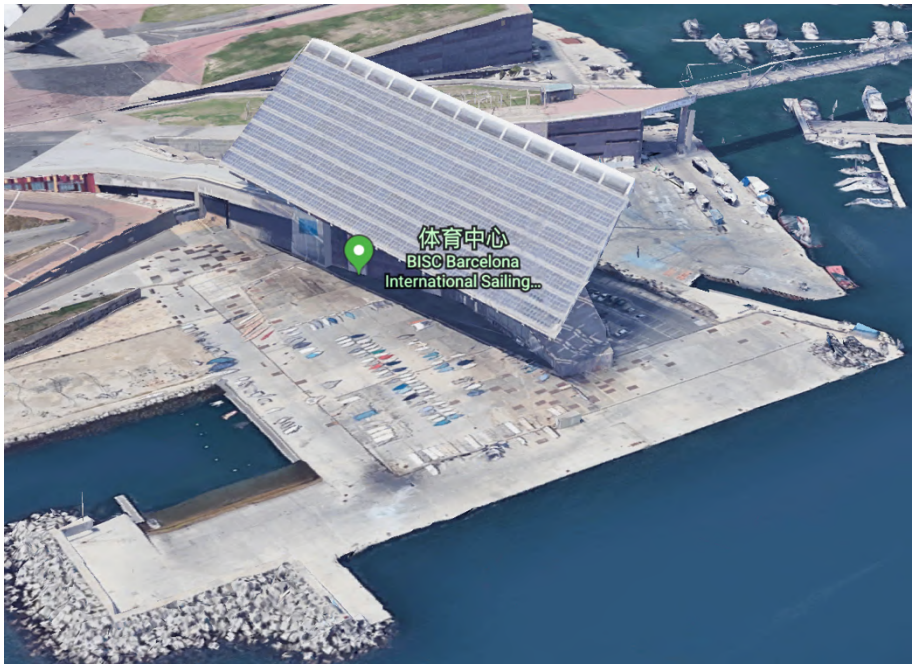

Figure 45. International sailing center of Barcelona

Besós River & Litoral Beach

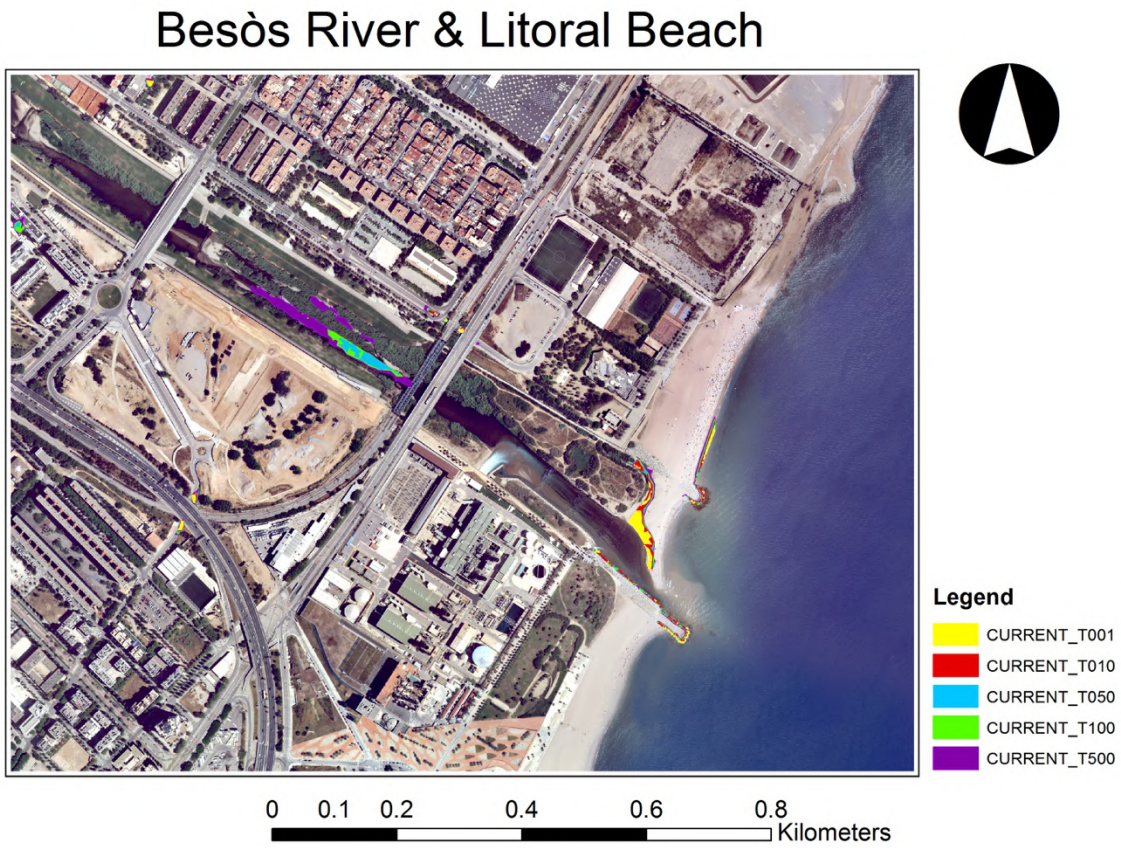

Figure 46. Current scenario + Storm Surge projection at Besós river & Litoral beach

In this part, the flood situation will be not as serious as previous parts, the influences are focusing on river bank, beach and breakwaters.

Even if during the most severe T500 storm surge, the river bank has no influence, as the impact polygons showing in the results map are located in the river, the water just cover the plants inside the Besós river. On the beach, the influence is smaller than other beaches, the maximum influence width is 8 meters. And the breakwaters can protect the inland perfectly all the time.

However, even though there is almost no physical influence on this area, the invisible influences cannot be negligible. The invasion of seawater would definitely cause changes in river ecosystems. Besides, the increased sea level would change the downstream boundary condition of Besós river, which can lead to river dynamic performance changing.

Summary

In this scenario, the vulnerable places focusing on harbors, especially the old harbor like Barcelona harbor and Fòrum harbor. The impact on beaches are impressive, almost all of the beach in Barcelona will exposure the shrinking risk to be by sea level rise and storm surges. The influence on two rivers is not that obvious compared with beaches and harbors, but the indirect impact needs to be taken into consideration carefully, such as ecosystem and dynamic performance after changes.

The influence on different area shows in following table: if the influence is big enough to affect the components not being able to use anymore, the fonts is in red; if there is influence but can still operate properly, the fonts is in black; if there is a blank means there is no influence in that return period. (all the influences are based on result map corrected by field trip)

Table 4. Influence results in current scenario + each storm surge in each area

		T1	T10	T50	T100	T500
current scenario + storm surge	**Estuary of Llobregat river**	beach	beach	beach	beach	beach
		green space	green space	green space	green space	green space
		breakwater	breakwater	breakwater	breakwater	breakwater
	Llobregat river	right river bank park	right river bank park	right river bank park	right river bank park	right river bank park
	Llobregat river left harbor	green space	green space	green space	green space	green space
			small pier	small pier	small pier	small pier
		breakwaters	breakwaters	breakwaters	breakwaters	breakwaters
	Oil Harbor	8 docks	8 docks	8 docks	8 docks	8 docks
		jetty	jetty	jetty	jetty	jetty
				west discharging platform	west discharging platform	west discharging platform
						north discharging platform
	Front Harbor				quay	quay
		repairing dock*	repairing dock*	repairing dock*	repairing dock*	repairing dock*
				3 pier	3 pier	3 pier

			2 parking areas	2 parking areas	2 parking areas	2 parking areas
	Barcelona Harbor		quay	quay	quay	quay
		7 piers	7 piers	7 piers	7 piers	7 piers
		repairing docks*	repairing docks*	repairing docks*	repairing docks*	repairing docks*
	Barceloneta beach group	beaches	beaches	beaches	beaches	beaches
		north breakwater	north breakwater	north breakwater	north breakwater	north breakwater
		middle breakwater	middle breakwater	middle breakwater	middle breakwater	middle breakwater
	Olympic Harbor	breakwaters	breakwaters	breakwaters	breakwaters	breakwaters
					gas station	gas station
					parking area	parking area
						sailboat garage
			quay	quay	quay	quay
	Nova lcària beach	beach	beach	beach	beach	beach
	Llevant beach group & Océanos Buceo Profesional	inclined platform	inclined platform	inclined platform	inclined platform	inclined platform
		breakwaters	breakwaters	breakwaters	breakwaters	breakwaters
		beach	beach	beach	beach	beach
	Fòrum swimming zone & Fòrum Harbor	swimming platforms	swimming platforms	swimming platforms	swimming platforms	swimming platforms
		jetty	jetty	jetty	jetty	jetty
						docks
					roads	roads
			fixed pier	fixed pier	fixed pier	fixed pier
				sailing center platform	sailing center platform	sailing center platform
			quay	quay	quay	quay
	besós river & Litoral beach	beach	beach	beach	beach	beach
		breakwaters	breakwaters	breakwaters	breakwaters	breakwaters

*Note: 1. * means its flooding situation depends on its status. 2. Influence in black and damages in red.

50% Sea Level Rise projection scenario + Storm Surge

In this scenario, the sea level rise projection uses the middle level result of nine CMIP 5 models under RCP8.5, which is 0.05 meters. The orange, green, blue, pink and red polygons in following figures show the impact of T1, T10, T50, T100 and T500 storm surge respectively of the future scenario middle level projection. The table shows the height of sea level rise, different time return period storm surge and their sum. Under this scenario, there are 12 parts in Barcelona coastal area can be more or less flooded, each of them has different risk level.

Table 5. Water increase height in 50% SLR + Storm Surge projection

Return Period	Future scenario (2100)
	50% SLR + Storm Surge
T1	0.05+0.51=0.56
T10	0.05+0.74=0.79
T50	0.05+0.94=0.99
T100	0.05+1.07=1.12
T500	0.05+1.31=1.36

*Note: the unite of table is meter

The analysis description following will be divided according to areas as the analysis above, which means all the different return periods storm surge is overlapping into one location map and the analysis on these storm surge will describe together.

Llobregat River Estuary

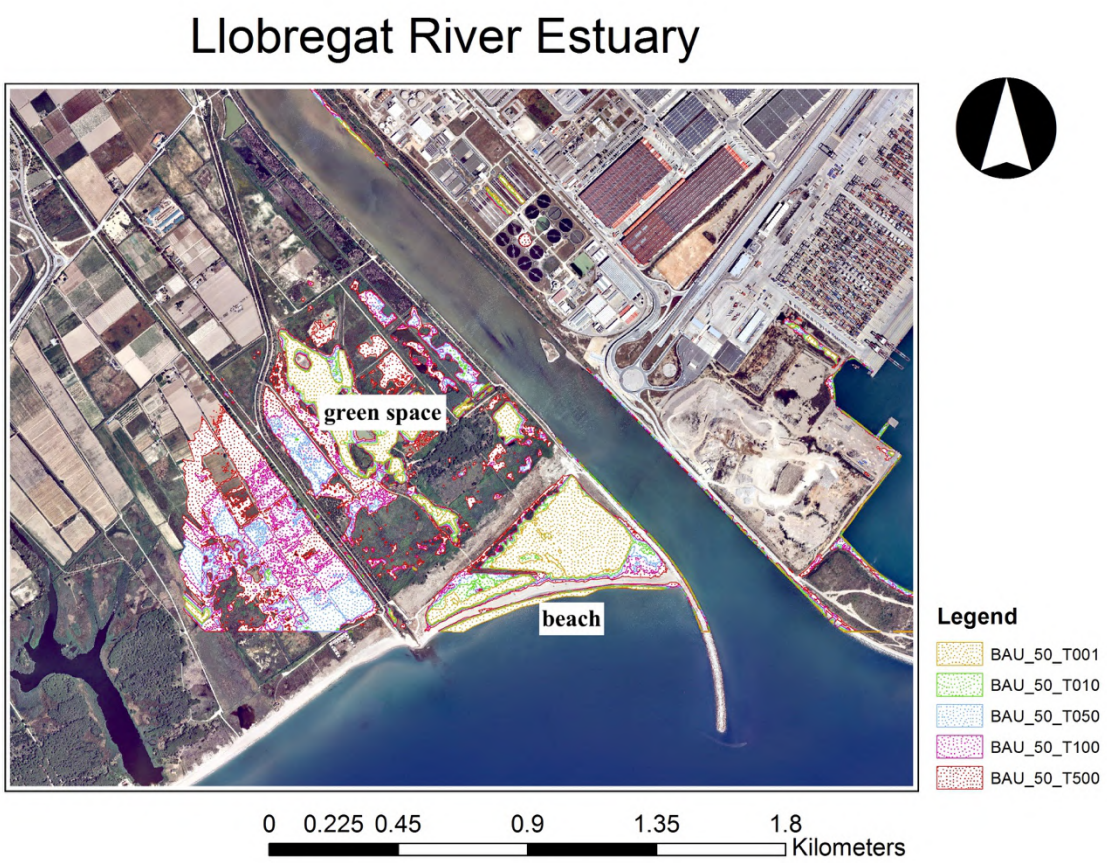

Figure 47. 50% SLR + Storm Surge projection at Llobregat river estuary

In this area, the influences are much more severe than current scenario. The vulnerable places are also focusing on green space and beach.

The beach can be flooded around 20 meters to 25 meters on average in different storm surges. And the green space right behind the beach is almost completely flooded. The green space along the river bank also have big damages, nearly 70% green space in that area will be covered by water in the most significant storm surge event. As the same as previous scenario, the reason for water invading into the green space is not directly coming from sea, it is because of the low elevation in this area instead. Comparing to current scenario, the influence on green space has extended to the part on the west, it could be imagined that the ecosystem and biology environment damages would be more serious.

The breakwaters are quite safe, the water cannot cross them in this scenario as well.

Llobregat River

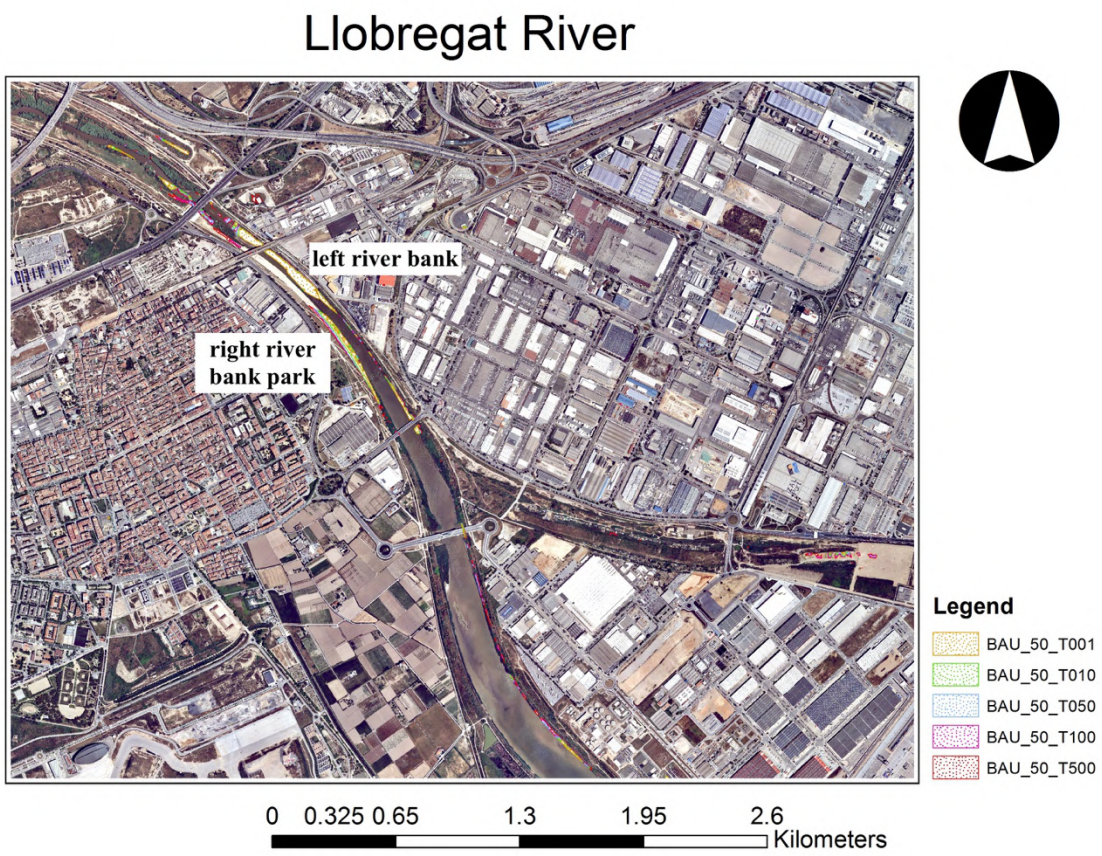

Figure 48. 50% SLR + Storm Surge projection at Llobregat river

In the Llobregat river, the risky locations do not change much compared to current scenario, but the length of influence has increased.

The influences are located at a distance of 4 to 6 kilometers from the estuary, focusing on right river bank park and plants in the river. The water can flood into the park around 20 meters to 40 meters on average in different storm surges. The left bank can still protect the left part perfectly, there is almost no risk that water can cross the left river bank. Additionally, the sea level rise would also lead to a big change of downstream boundary condition, causing the different dynamic performance of the river. The more details of changes need more hydraulic simulation to specific.

Llobregat River Left Bank Harbor

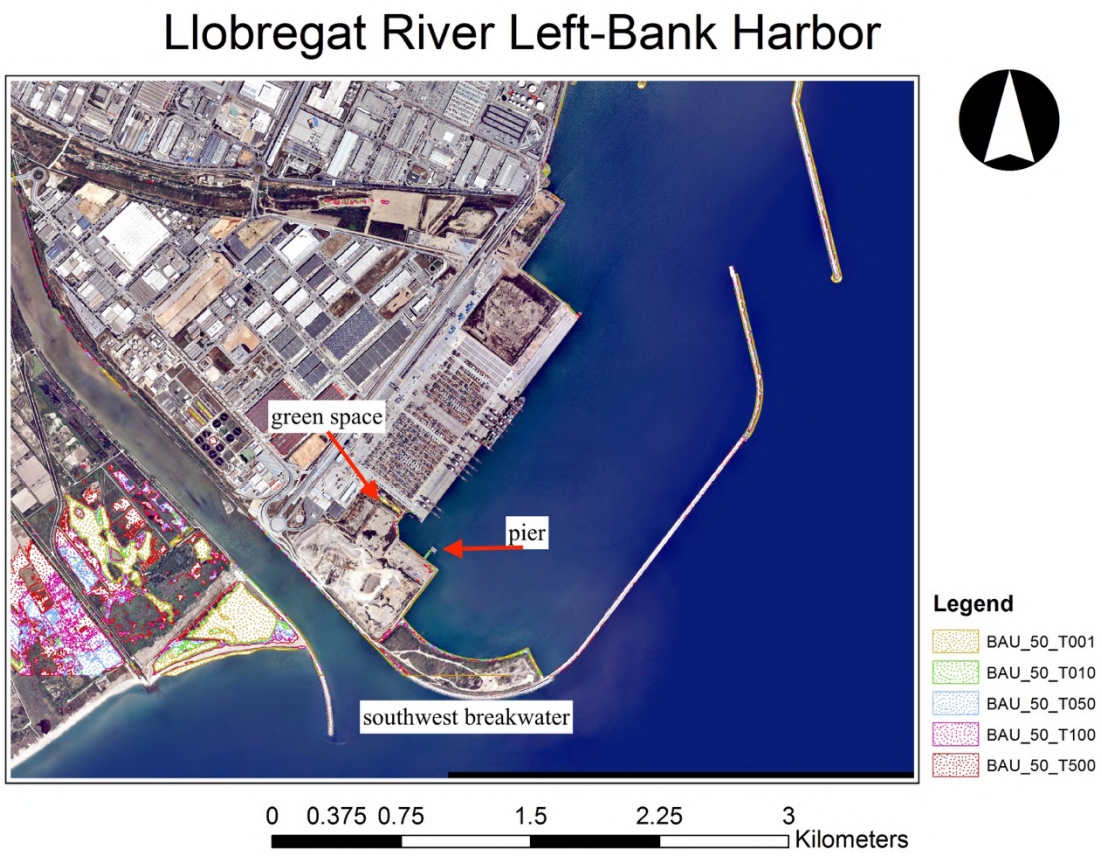

Figure 49. 50% SLR + Storm Surge projection at Llobregat river left-bank harbor

In this area, the vulnerable places are as the same as current scenario, including breakwaters located on the southwest and northeast, the small pier and the green space next to the quay.

During the T500 storm surge in this scenario, sea water can cross the northeast breakwater and enter into the harbor. The breakwater located at the southwest is safer than previous one, even if water can cross the breakwaters during T500 storm surge as well, it cannot flood the whole green space. Hence, the breakwater and green space can protect the harbor quite well. The small pier would be covered by water starting from T100 storm surge, even influence the quay link to it. And the green space next to quay would be flooded starting from T10 storm surge, if considering construction project in this area, a land-filling for increasing the elevation is necessary.

Oil Harbor

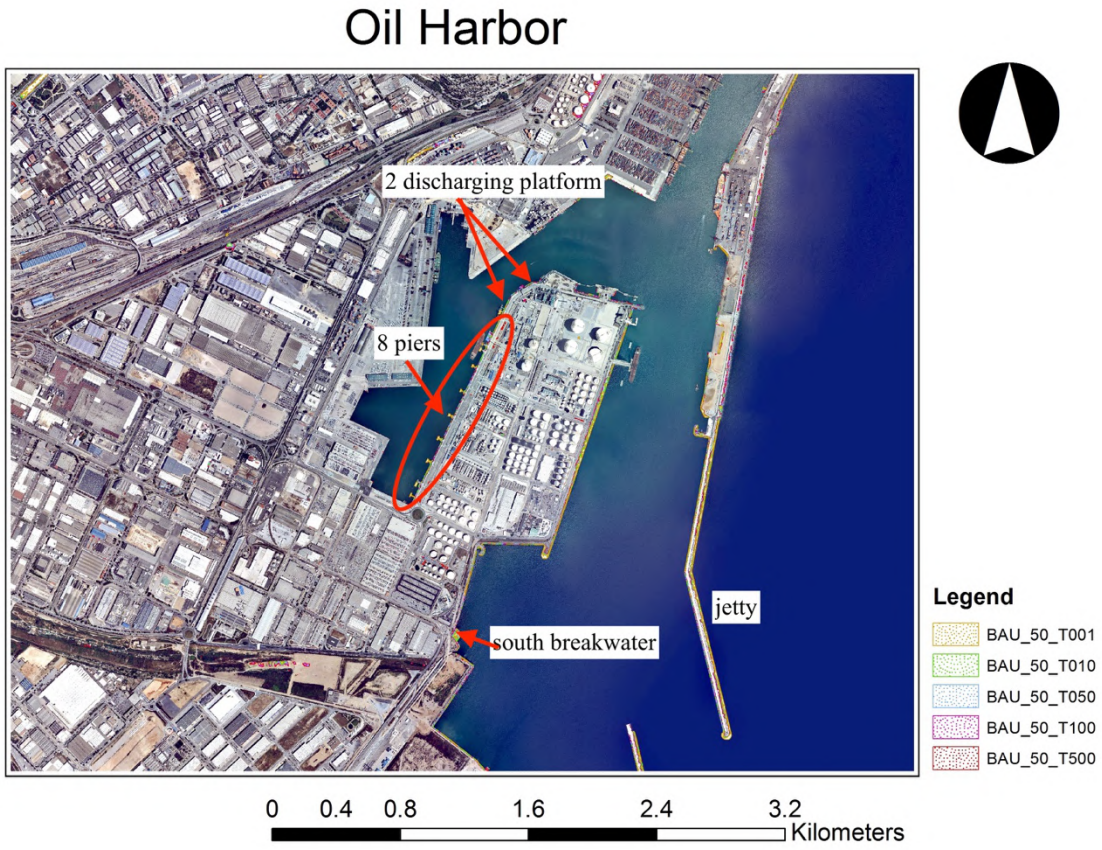

Figure 50. 50% SLR + Storm Surge projection at oil harbor

In the oil harbor, besides the vulnerable places in current scenario, there are three more places can encounter the risk easily, including breakwaters located on the south of the harbor, the east side quay and the jetty on the east.

The 8 piers in this harbor would be covered by water starting from T1 storm surge. Two discharging platforms located on northwest can get flooded starting from T50 and T100 storm surge respectively. The breakwaters on the south part cannot protect the inland anymore, during T500 storm surge, the water can enter into interior. Luckily, the water cannot flood too wide to impact the important construction and equipment inside. Along the east quay of oil harbor, the whole length of quay has a big risk when encounter T500 storm surge, the water almost crosses the breakwater and enter into harbor. The same happened to jetty on the east, during T500 storm surge, the water almost cross it. Even if the results map does not show the water would totally flood over them, there still has a big risk that it cannot protect the harbor anymore during T500 storm surge.

Front Harbor

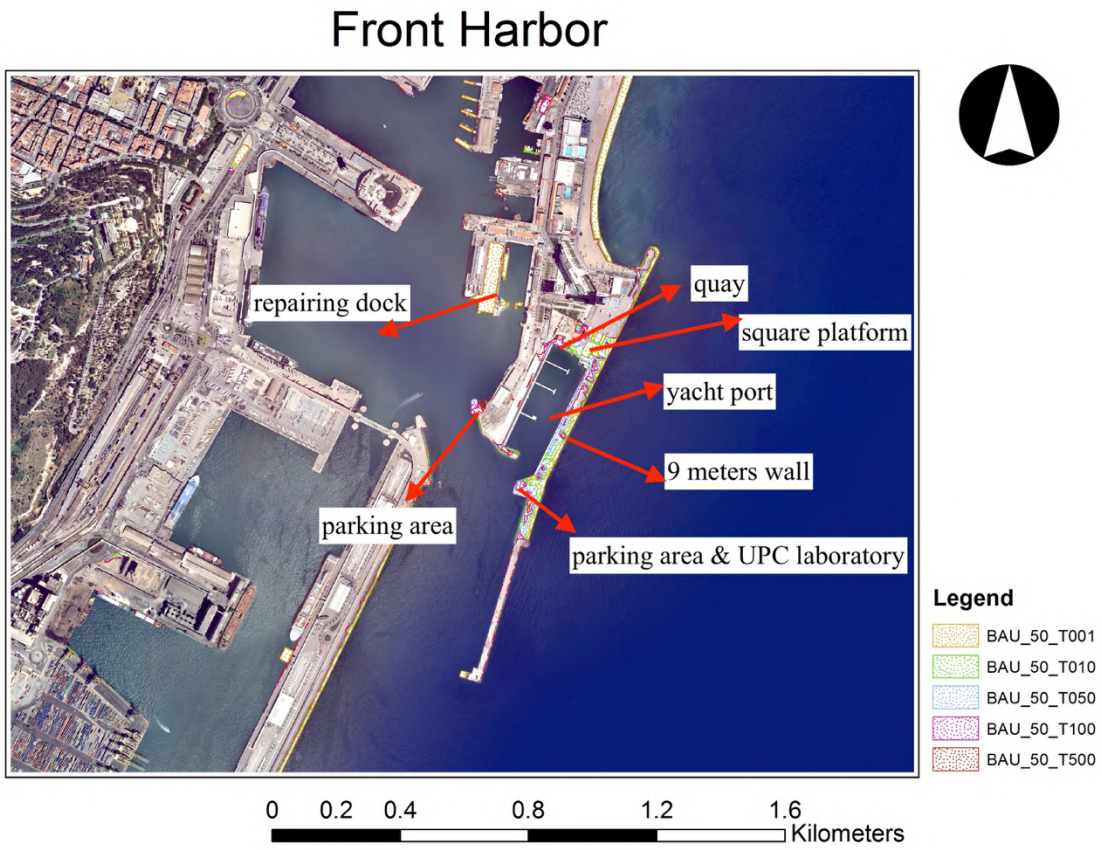

Figure 51. 50% SLR + Storm Surge projection at Front harbor

In Front harbor, the vulnerable places are similar to current scenario, including repairing dock, 3 piers inside the yacht, quay, breakwaters and parking areas.

The flooding situation in repairing dock still depends on its status. The 3 piers inside yacht port would be flooded starting from T50 storm surge. Even if it does not show in the map, according to the field trip mentioned before, the height of piers are around 0.8 meters, they can be covered by water when water would increase higher than 0.8 meters. The quay inside the port harbor also can be flooded starting from T50 storm surge. The breakwater located at the south of yacht port have a risk to be flooded starting from T100 storm surge. Two parking areas all would get flooded starting from T10 storm surge. It is notable that one of the parking areas which also has a UPC laboratory, the flood may cause equipment damages or economic losses as well.

As mentioned before, which is also applied in this scenario, the influences showed on the results map about breakwater on the east and the square platform located on the north of yacht port are not accurate. The breakwater already be built as an 9 meters wall and the square platform there also constructed a three-floors building. Hence, there is no more influence on these two parts in this scenario.

Figure 52. Parking are with UPC laboratory

Barcelona Harbor

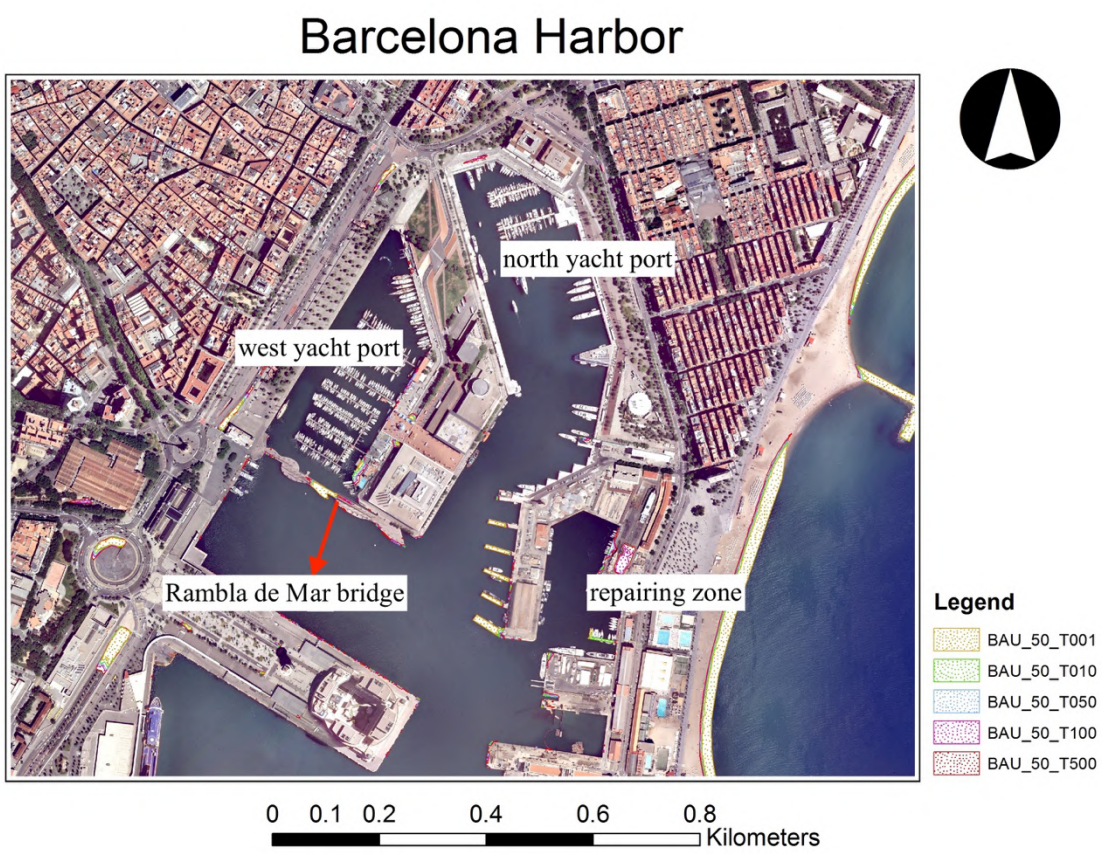

Figure 53. 50% SLR + Storm Surge projection at Barcelona harbor

In Barcelona harbor, the vulnerable places are still focusing on yacht port and repairing zone. In the yacht port, the quay along the east part can be influenced by water starting from T1 storm surge, but the situation is not serious, even if in T500 storm surge, the quay still cannot be fully flooded, only small part along the water can get influences. However, in repairing zone, the situation is much more serious. The 7 piers in this part all will be completely flooded starting from T1 storm surge, and two repairing dock also can get influence, but it depends on the working status.

The tourist bridge Rambla de Mar in this scenario still could not be influenced, according to the measurement, if the bridge is flooded, the water height needs reach to at least 1.5 meters.

Barceloneta Beach Group

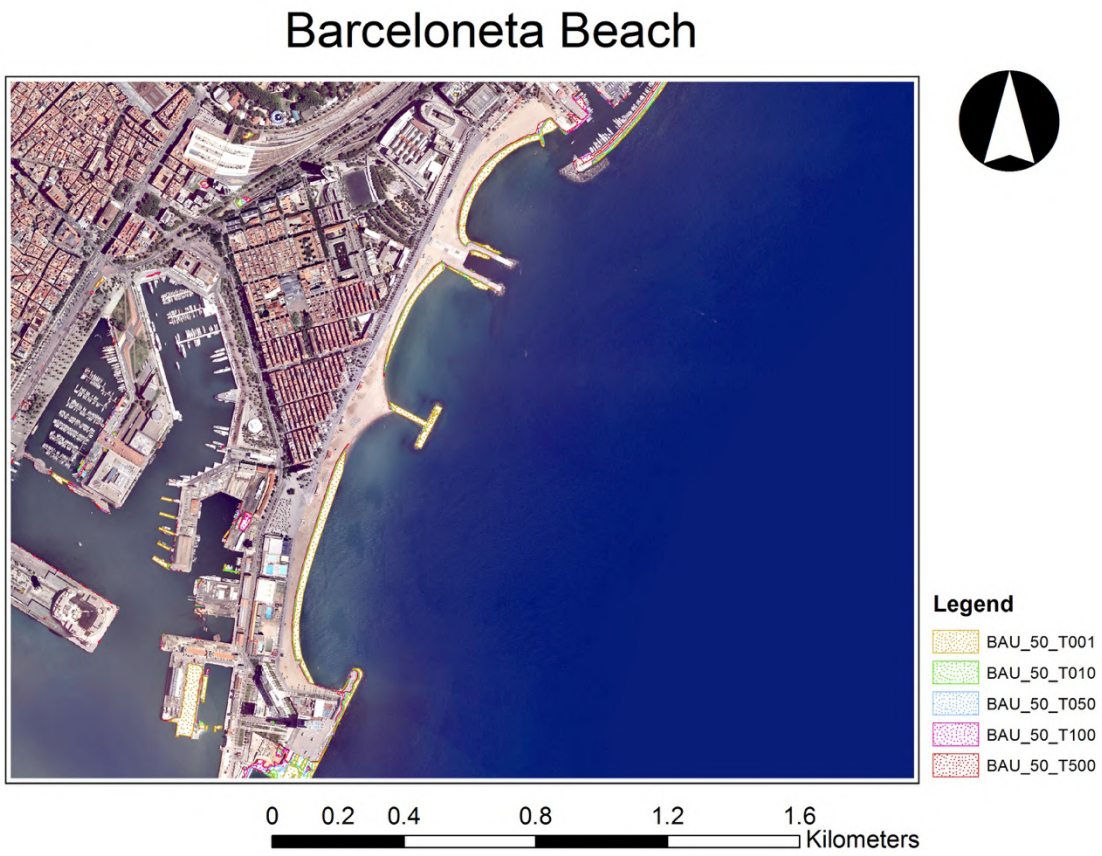

Figure 54. 50% SLR + Storm Surge projection at Barcelona beach

In this area, three part of beaches have different influence. The first part of beach would shrink 20 meters to 25 meters on average from T1 to T500 storm surge; the second one, better than first one, the width of influences are about 15 meters to 20 meters on average in different storm surge; the last one would be flooded about 23 meters to 28 meters on average. The breakwaters separating the first and the second part of beaches would be fully covered by water starting from T1 storm surge; the one located at the most north part in this area would be fully covered starting from T10 storm surge.

Olympic Harbor

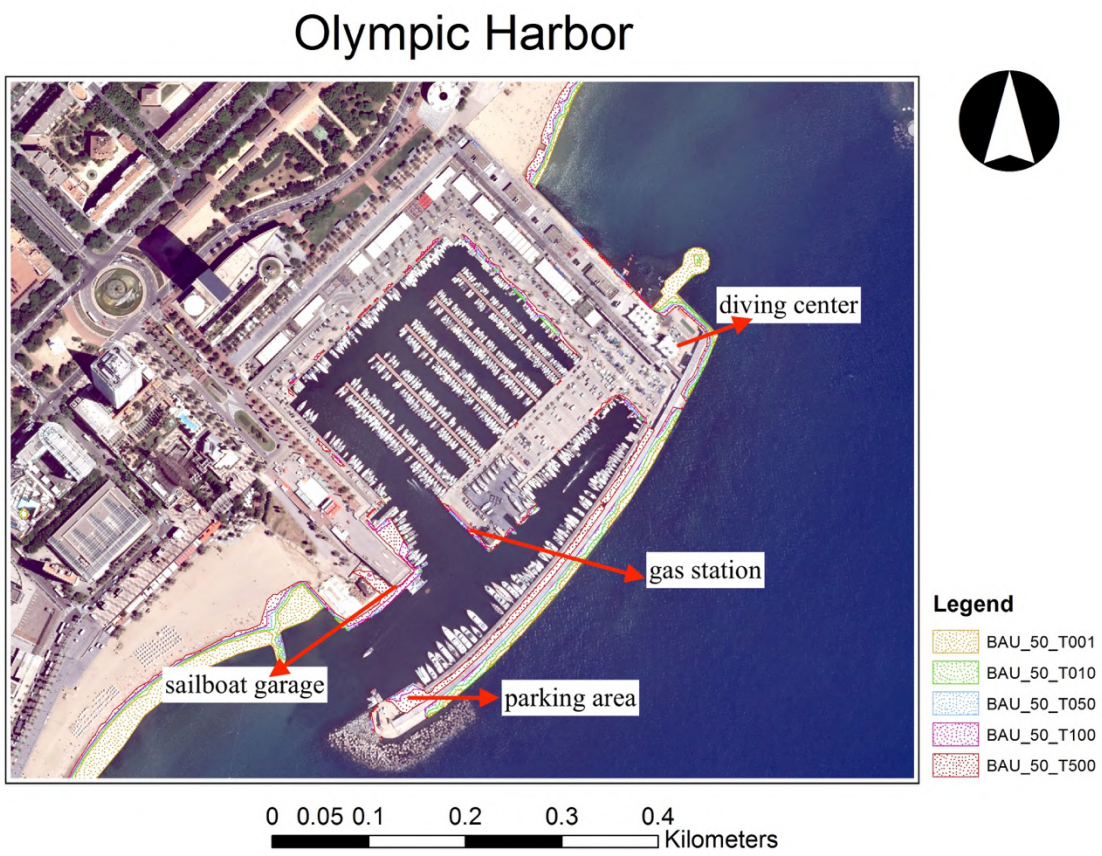

Figure 55. 50% SLR + Storm Surge projection at Olympic harbor

The Olympic harbor is much more vulnerable than before. The quay along the breakwater, gas station, sailboat garage, parking area and the quay in the yacht port all have different influences.

The quay along the breakwaters located at the southeast of harbor can be flooded during T500 storm surge. And the breakwater, which are steps actually, will be covered by water starting from T100 storm surge, which means the both sides of that part, the quay and the steps, all would be flooded. Besides, the parking area next to the quay, due to the same elevation, would also be flooded starting from T100 storm surge. The sailboat garage on the west would get influences starting from T100 storm surge, and it would be fully covered by water during the T500 storm surge. It also influences the quay on the east of sailboat garage, will be flooded starting from the same return period storm surge. The quay inside harbor would get influence starting from T10 storm surge, but the influence area does not extend too

much. The gas station would be flooded starting from T50 storm surge, which in this part is the riskiest part can lead to leaking problem. The breakwaters on the east of harbor would be covered by water starting from T100 storm surge. Luckily, the slope path extending to the sea used for diving does not have much influence, the diving center is still safe under this scenario.

Figure 56. The quay, parking area and steps in Olympic harbor

Nova Lcaria Beach

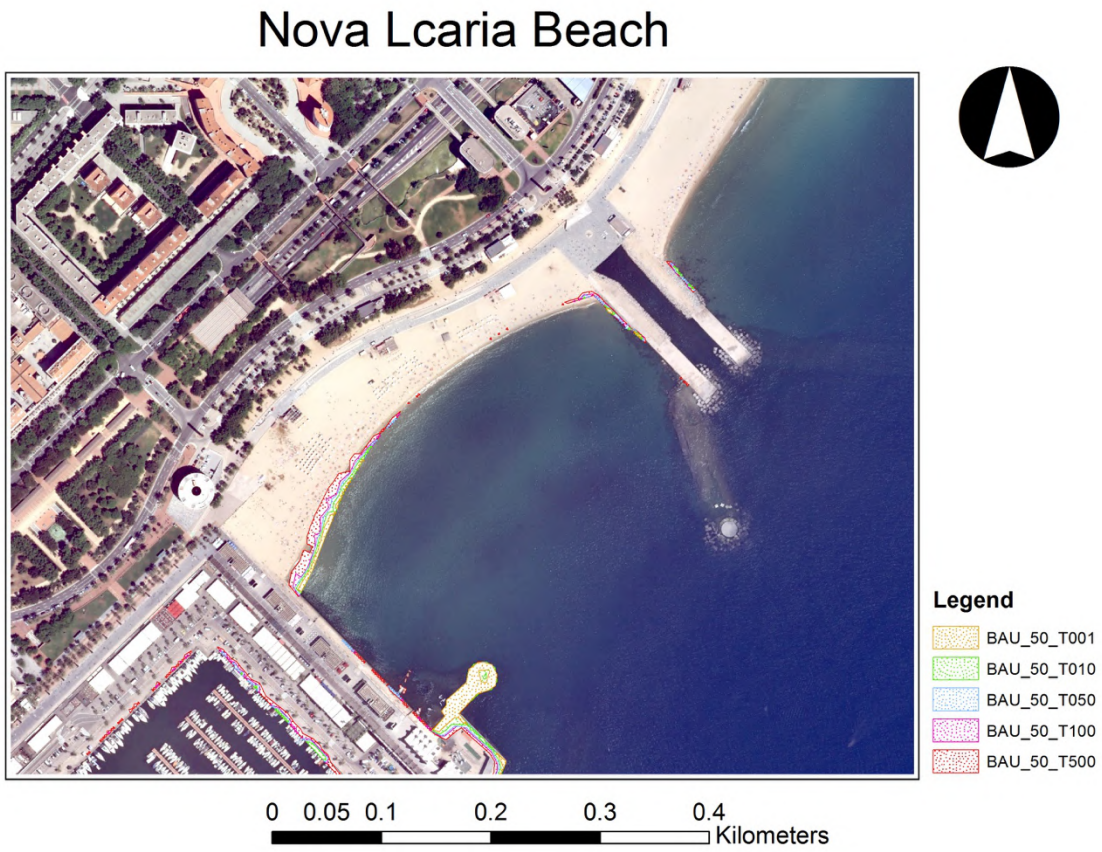

Figure 57. 50% SLR + Storm Surge projection at Nova Lcaria beach

On this beach, the influence mainly located on the west, the maximum flood width is around 16 meters.

Llevant Beach Group& Océanos Buceo Profesional

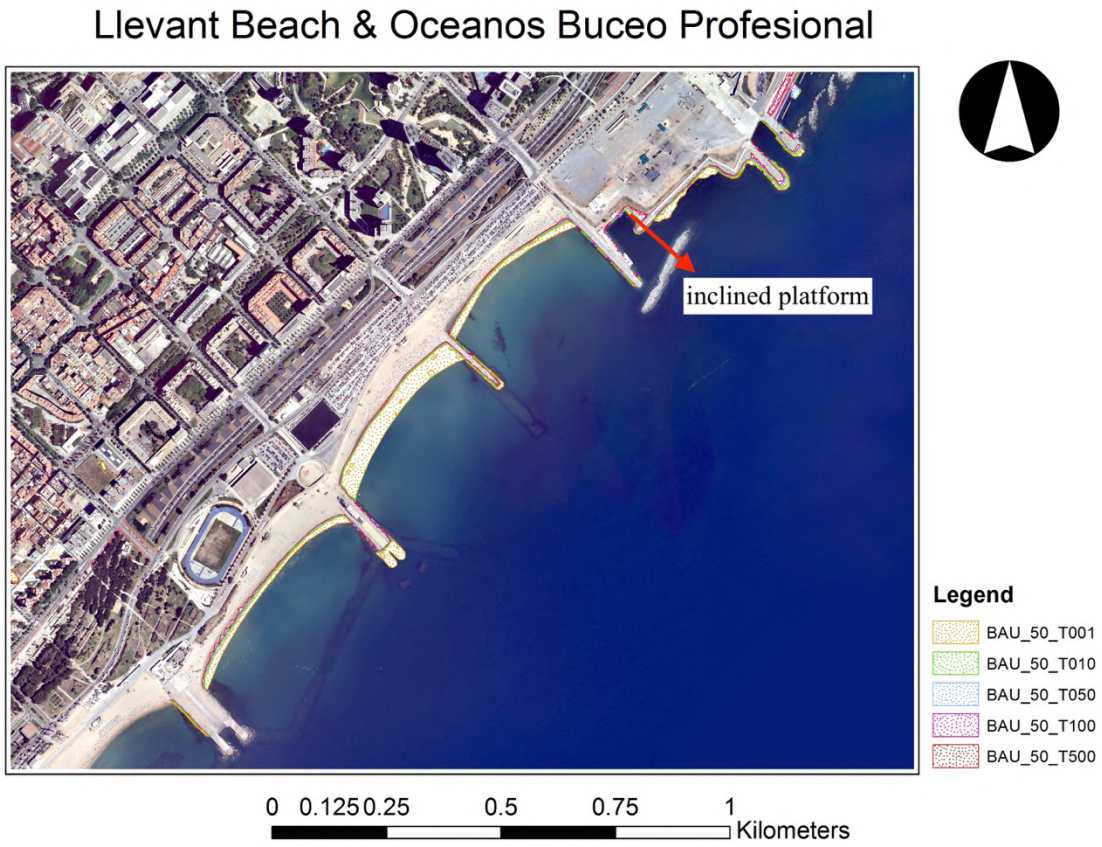

Figure 58. 50% SLR + Storm Surge projection at Llevant beach & Océanos buceo profesional

In this part, the most vulnerable part is also the middle part of beaches, the maximum width of influence during T500 storm surge is about 40 meters, the first and the third part are about 18 meters. The inclined platform in Océanos Buceo Profesional has influence about 20 meters on average during T500 storm surge.

Fòrum Swimming Zone & Fòrum Harbor

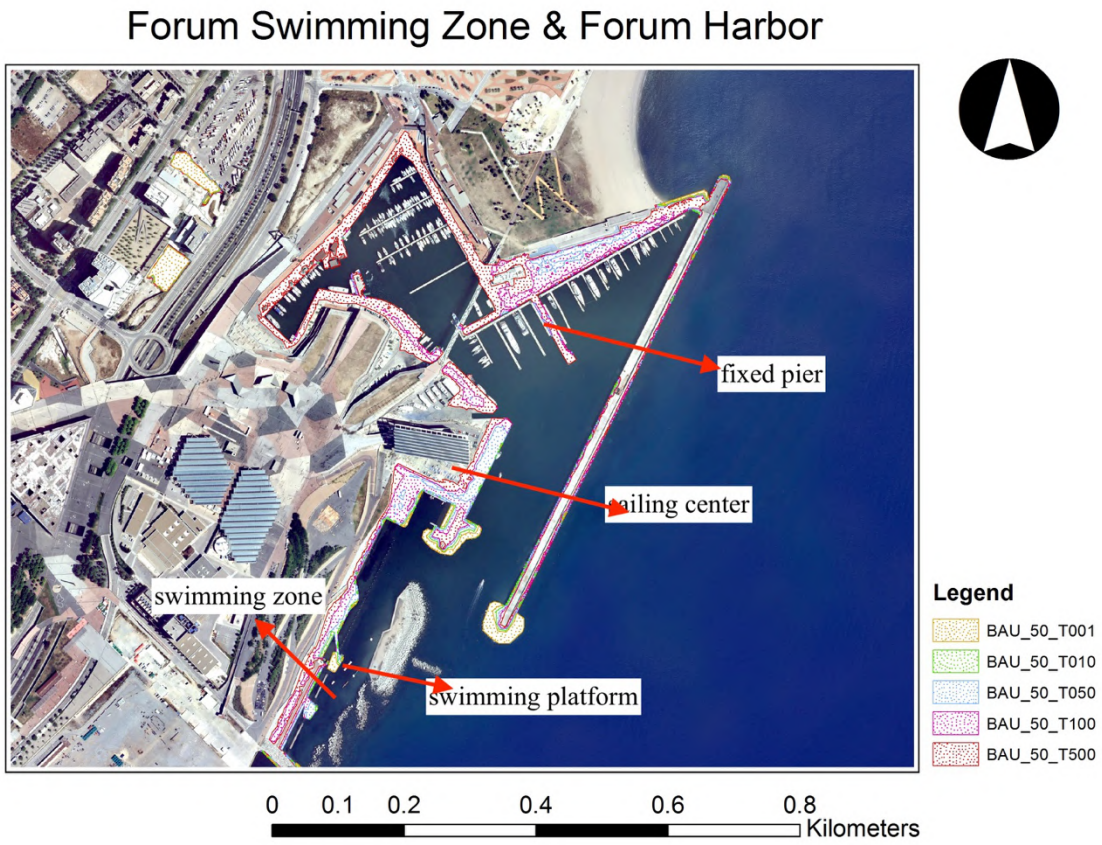

Figure 59. 50% SLR projection + Storm Surge at Fòrum swimming zone & Fòrum harbor

This part is the most vulnerable place around the whole coastal area in Barcelona.

In swimming zone, the swimming platforms would be fully covered by water starting from T1 storm surge, the pathway along the water would be flooded starting from T100 storm surge. About the sailing center next to swimming zone, the bottom floor would be completely flooded starting from T50 storm surge. The quay along the whole Fòrum harbor can be flooded starting from T100 storm surge. The same happened to the fixed quay since it elevation is the same as the quay. And the road including parking area and green space right behind the quay on the north of harbor will be flooded starting from T100 storm surge as well.

On conclusion, the only part will not be flooded in this scenario, is the jetty on the east. However, since the whole harbor will be totally flooded if without any adaptation, there is no more point that jetty still can work well.

Besós River & Litoral Beach

Figure 60. 50% SLR + Storm Surge projection at Besós river & Litoral beach

The influence on this area is much more moderate compared to all of the areas mentioned above. The vulnerable places are focusing on river and beach. The maximum influence on the beach during T500 storm surge is about 9 meters. And the influence in the river only focusing on plants area, which cannot cause any risk on river bank. But the influence on ecosystem is not negligible, as well as the impact on the dynamic performance due to the changing of downstream boundary condition of the Besós river.

Summary

In this scenario, the impact of each area has expanded and the number of vulnerable parts has increased. The most serious areas are concentrated in the harbors. Due to some of them are built up in the early time, the influence on these harbors are impressive. If there are no on-time adaptation measures on components of harbors, especially in the port of Barcelona Harbor and Fòrum Harbor, there would cause irreparable economic losses.

Although the impact on the two rivers is not direct, the indirect effects on them are not negligible as well. For example, changes in downstream boundary of the river will change the dynamic performance of the entire river, and the ecosystem in the downstream part is facing important threaten due to the seawater intrusion.

For the impact on the beach, although the impact is relatively simple, it is also very surprising. In the most serious areas, the Llevant beach group, it can be reduced by about 40 meters, which is a huge threaten to Barcelona's tourism attraction.

The influence on different area shows in following table: if the influence is big enough to affect the components not being able to use anymore, the fonts is in red; if there is influence but can still operate properly, the fonts is in black; if there is a blank means there is no influence in that return period. (all the influences are based on result map corrected by field trip)

Table 6. Influence results of 50% SLR + each storm surge in each area

		T1	T10	T50	T100	T500
50% SLR + storm surge projection	**Estuary of Llobregat river**	beach	beach	beach	beach	beach
		green area	green area	green area	green area	green area
		breakwater	breakwater	breakwater	breakwater	breakwater
	Llobregat river	left river bank	left river bank	left river bank	left river bank	left river bank
		right river bank park	right river bank park	right river bank park	right river bank park	right river bank park
	Llobregat river left harbor	green space	green space	green space	green space	green space
			small pier	small pier	small pier	small pier
		breakwaters	breakwaters	breakwaters	breakwaters	breakwaters
	Oil Harbor	8 piers	8 piers	8 piers	8 piers	8 piers
		south breakwater	south breakwater	south breakwater	south breakwater	south breakwater

				west discharging platform	west discharging platform	west discharging platform
		east quay	east quay	east quay	east quay	east quay
		jetty	jetty	jetty	jetty	jetty
					north discharging platform	north discharging platform
	Front Harbor		3 piers	3 piers	3 piers	3 piers
		repairing dock*	repairing dock*	repairing dock*	repairing dock*	repairing dock*
		breakwaters	breakwaters	breakwaters	breakwaters	breakwaters
		2 parking areas	2 parking areas	2 parking areas	2 parking areas	2 parking areas
			quay	quay	quay	quay
	Barcelona Harbor	7 piers	7 piers	7 piers	7 piers	7 piers
		quay	quay	quay	quay	quay
		repairing docks*	repairing docks*	repairing docks*	repairing docks*	repairing docks*
	Barceloneta beach group	beach	beach	beach	beach	beach
		north breakwater	north breakwater	north breakwater	north breakwater	north breakwater
		middle breakwater	middle breakwater	middle breakwater	middle breakwater	middle breakwater
	Olympic Harbor	east breakwater	east breakwater	east breakwater	east breakwater	east breakwater
						quay on the breakwater
				gas station	gas station	gas station
				parking area	parking area	parking area
					sailboat garage	sailboat garage
		east breakwater	east breakwater	east breakwater	east breakwater	east breakwater
		fixed pier	fixed pier	fixed pier	fixed pier	fixed pier
		quay inside the yacht port	quay inside the yacht port	quay inside the yacht port	quay inside the yacht port	quay inside the yacht port
	Nova lcària beach	beach	beach	beach	beach	beach

	Llevant beach group & Océanos Buceo Profesional	inclined platform	inclined platform	inclined platform	inclined platform	inclined platform
		beach	beach	beach	beach	beach
	Fòrum swimming zone & Fòrum harbor	swimming platforms	swimming platforms	swimming platforms	swimming platforms	swimming platforms
		breakwaters	breakwaters	breakwaters	breakwaters	breakwaters
				docks	docks	docks
					roads	roads
			sailing center platform	sailing center platform	sailing center platform	sailing center platform
					road behind the quay	road behind the quay
			quay	quay	quay	quay
	besós river & Litoral beach	beach	beach	beach	beach	beach
		breakwaters	breakwaters	breakwaters	breakwaters	breakwaters

*Note: * means its flooding situation depends on its status.

90% Sea Level Rise projection scenario + Storm Surge

The data used for analysis in this scenario coming from the high-level result in nine CMIP5 models. The sea level rise will increase 0.32 meters and the sums after combining with different storm surges in this scenario, the totally increase of sea level, showing in following table. The green, blue, red, yellow, orange polygons with slash respectively in following images show the impact of T1, T10, T50, T100 and T500 storm surge respectively of the future scenario high level projection. There are 13 parts of area along the Barcelona coastal have impressive influence.

Table 7. Table 5. Water increase height in 90% SLR + Storm Surge projection

Return Period	Future scenario (2100)
	90% SLR + Storm Surge
T1	0.32+0.68=1.00
T10	0.32+0.9=1.22
T50	0.32+1.1=1.42
T100	0.32+1.24=1.56
T500	0.32+1.64=1.96

*Note: the unite of table is meter

The analysis description following will be divided according to areas as the analysis above, which means all the different return periods storm surge is overlapping into one location map and the analysis on these storm surge will describe together.

Llobregat River Estuary

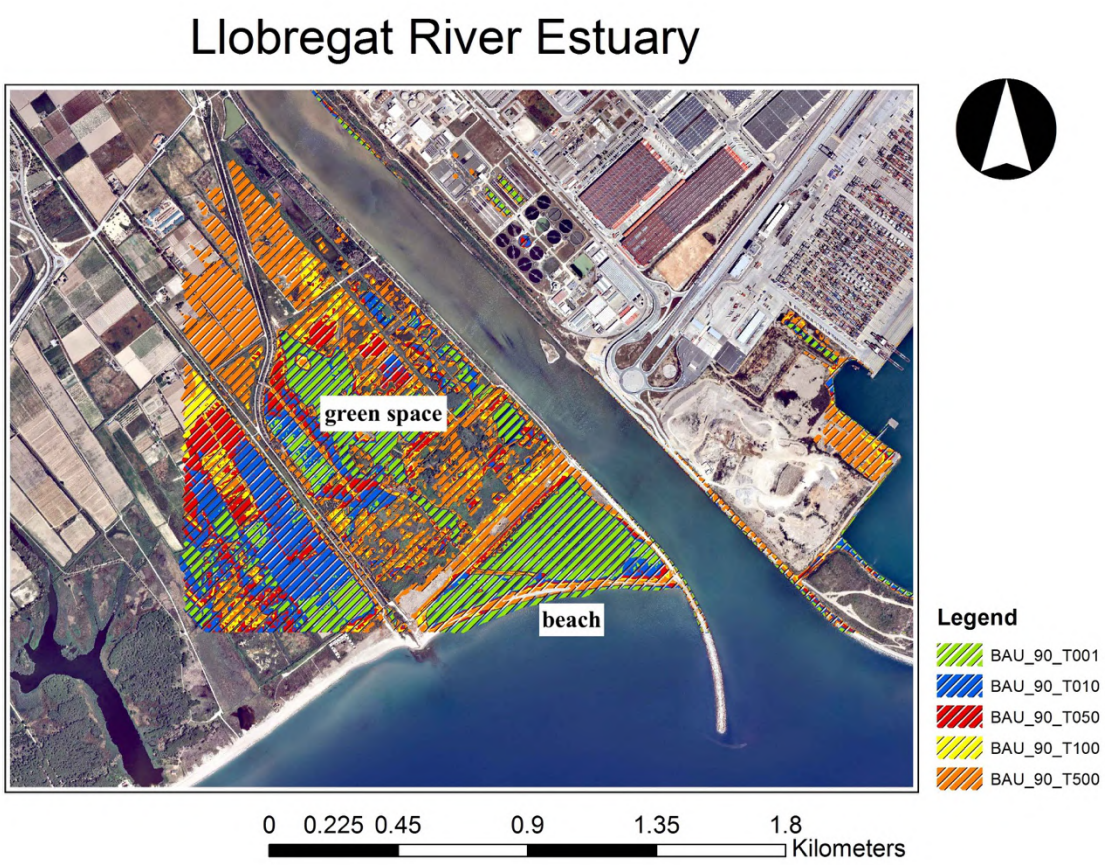

Figure 61. 90% SLR + Storm Surge projection at Llobregat river estuary

In this part, the most vulnerable place are still green space and beach. Impressively, the whole beach would get influence starting from T1 storm surge. During the T500 storm surge, the whole beach will be completely flooded and the water even can enter through the beach reach to the green space. The flooding area is around 1.4 km^2 in totally during T500 storm surge, additionally, the water can reach to some agriculture place in this part, causing economic losses.

Llobregat River

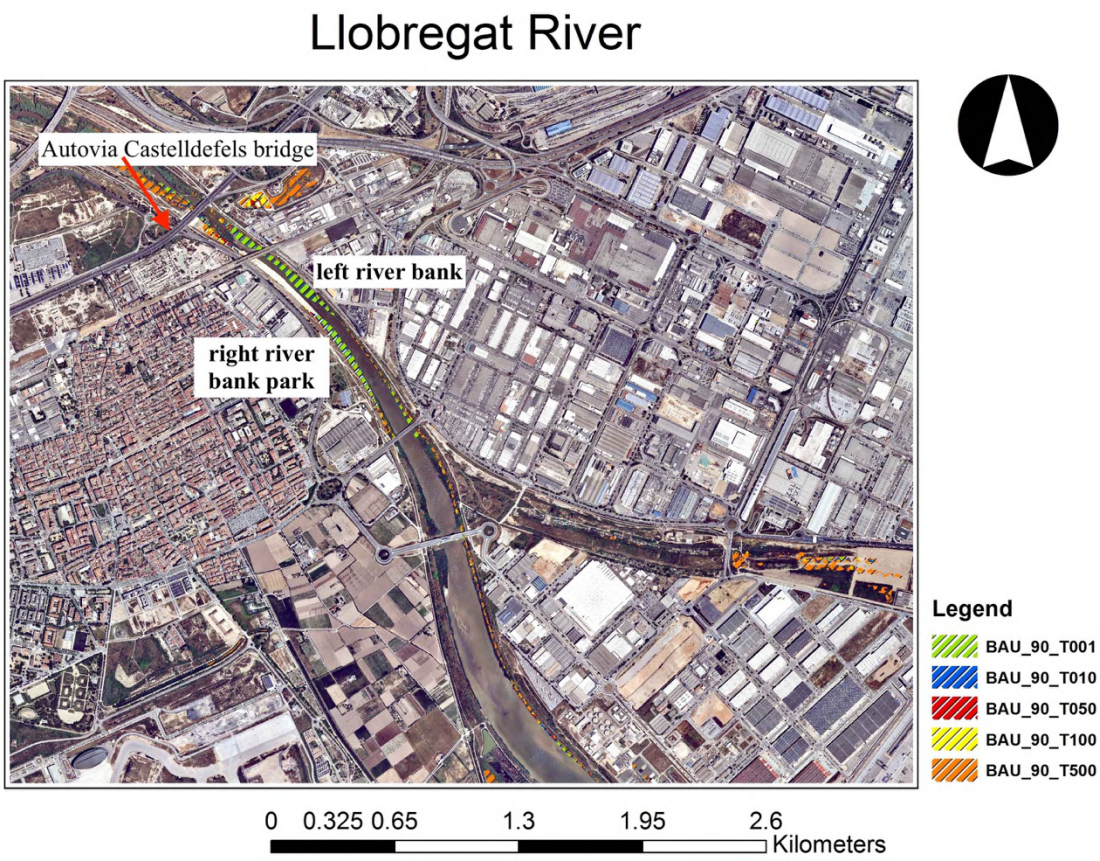

Figure 62. 90% SLR + Storm Surge projection at Llobregat river

In Llobregat river, the flood area tends to expand to upstream. The vulnerable places are still focusing on right bank park. The flooding width is around 33 meters to 40 meters on average during different storm surges in this park. The new influences appear at the both sides of the bridge named Autovia Castelldefels. On the left bank, the water can just cover the plant inside the river and has no influence to the river bank.

Additionally, the sea level rise also will have more significant change on downstream boundary condition, causing the different dynamic performance of the river as well as the ecosystem at downstream. The more details of changes need more hydraulic and hydrology simulation to specific.

Llobregat River Left Bank Harbor

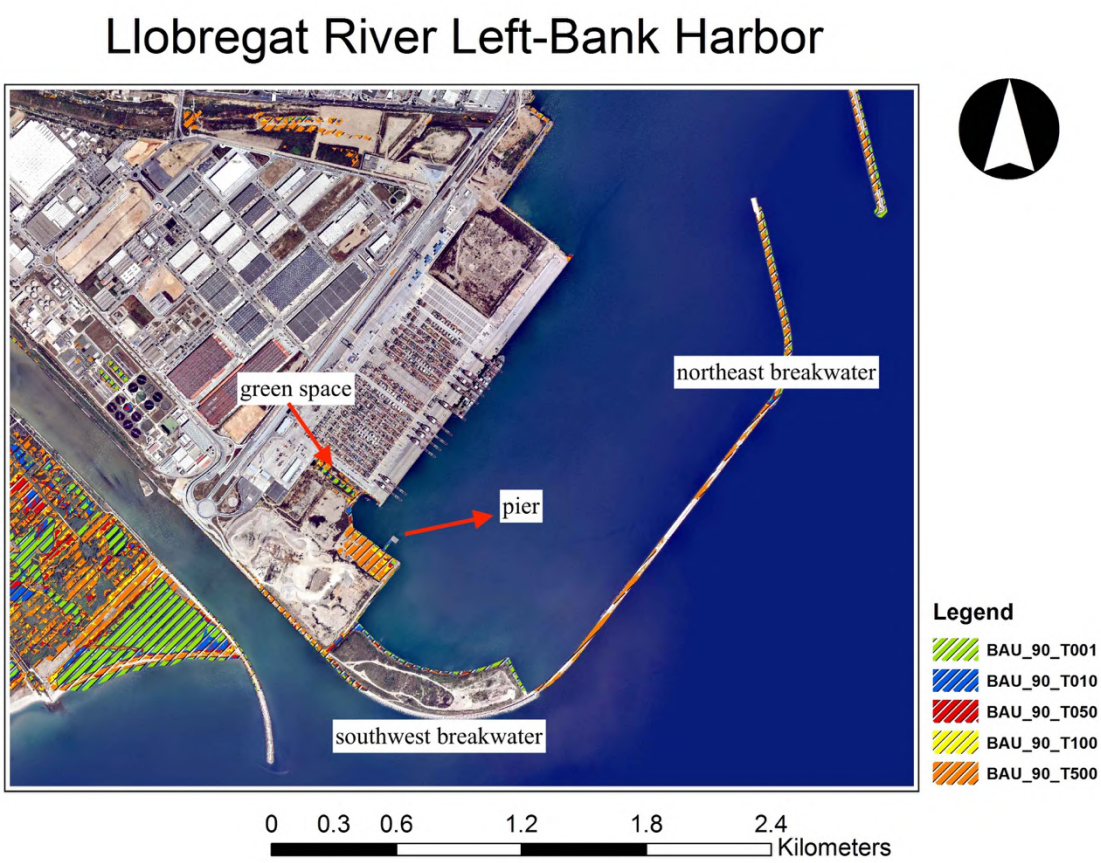

Figure 63. 90% SLR + Storm Surge projection at Llobregat river Left-bank Harbor

In this part, every components would easily get flooded even if during a short return period storm surge. The small pier on the west will be covered by water starting from T10 storm surge, and with the storm surge level increasing, the entire platform right behind the pier will be flooded. The green space next to the quay can be flooded starting from T1 storm surge. And the whole breakwaters except the part on the southwest have risk to be flooded starting from T100 storm surge, which means they cannot be used for protecting this harbor anymore during T100 and T500 storm surge.

Oil Harbor

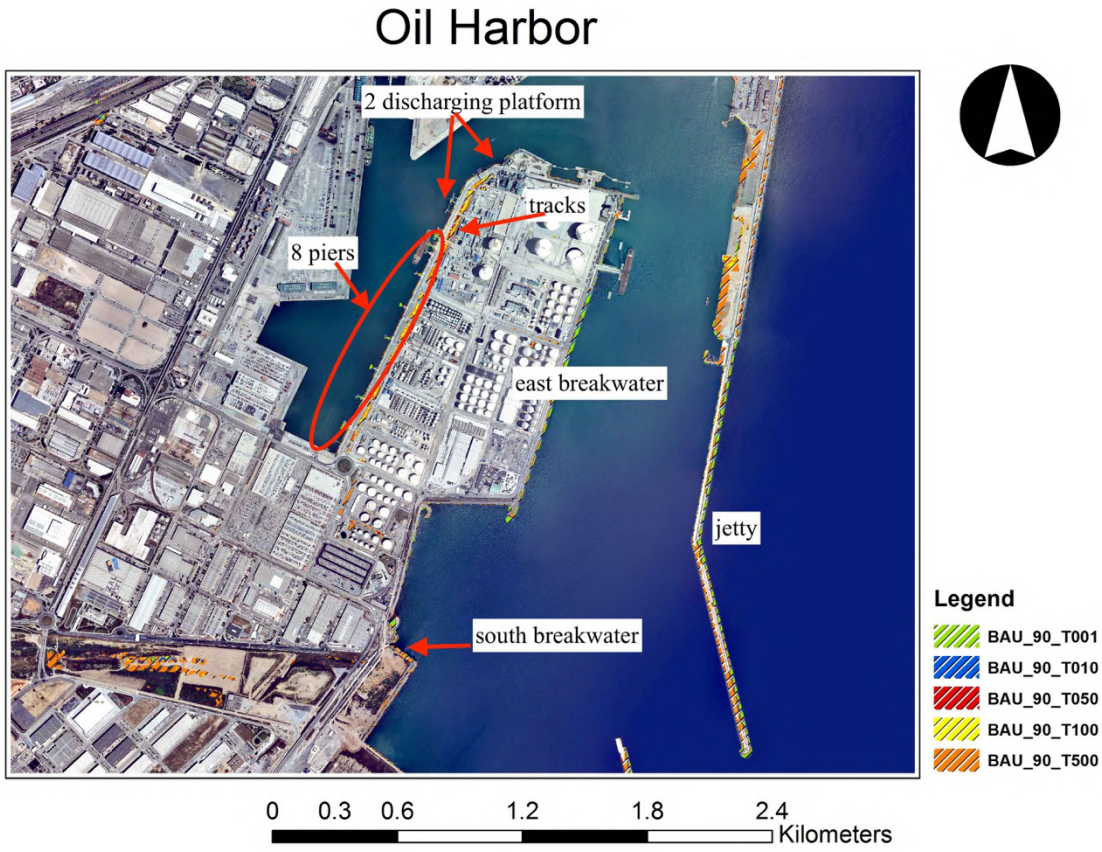

Figure 64. 90% SLR + Storm Surge projection at Oil Harbor

The same as previous scenarios, piers, breakwaters and 2 discharging platforms would get influences. Besides, the tracks, east quay and jetty are three new place can get flooded in this scenario.

The 8 piers would be completely flooded starting from T1 storm surge, two discharging platforms can be flooded starting from T1 and T10 storm surge respectively and the breakwaters on the south would be crossed by water starting from T1 storm surge leading to a risk to destroy the parking area behind.

And there are three more places will get influence in this scenario. There is a track facility located behind the piers that may be used for transporting large equipment or cargo. Its elevation is lower than road, and the seawater can infiltrate from the bottom to submerge these tracks starting from T100 storm surge. Starting from T10 storm surge, the sea water can cross the breakwaters on the east side of the harbor and enter into the road. And the

breakwaters for protecting the jetty on the east also will be flooded during T500 storm surge, the quays located on it would be covered by water.

Figure 65. Tracks behind the piers in the oil harbor

Figure 66. Quay along the jetty in oil harbor

Container Harbor

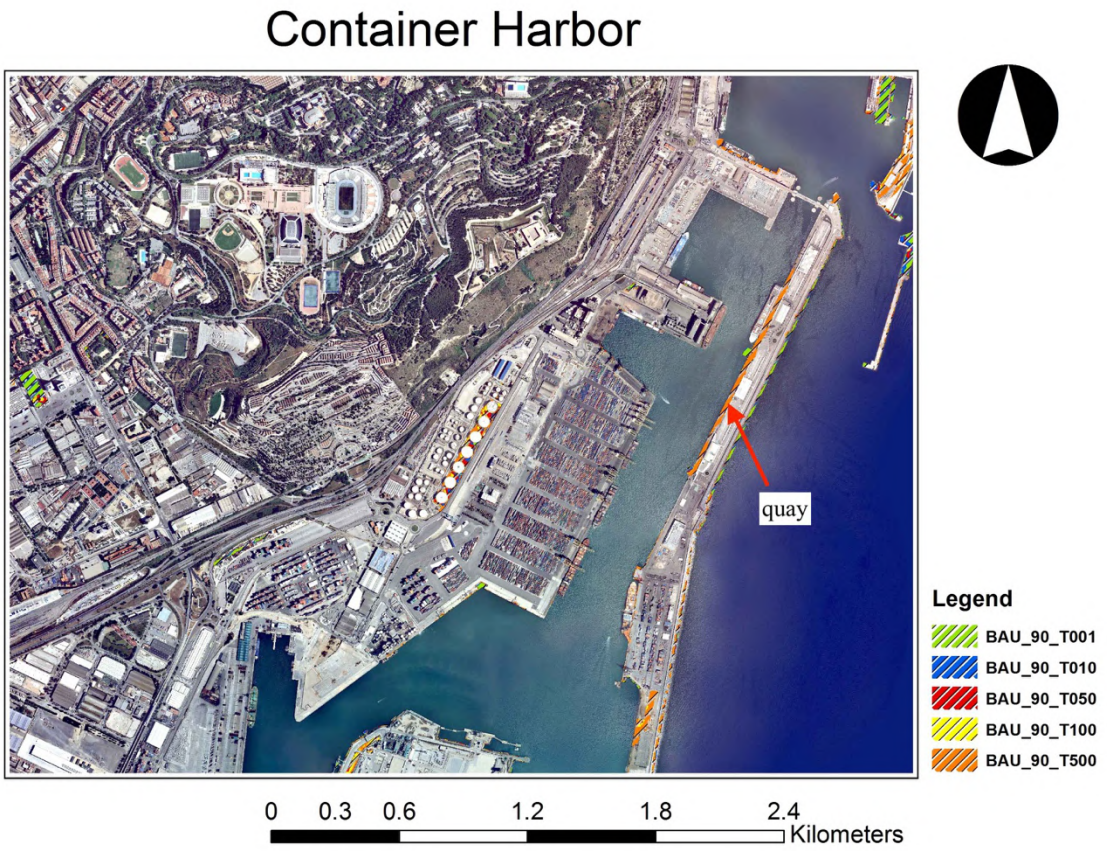

Figure 67. 90% SLR + Storm Surge projection at Container Harbor

The most vulnerable place in this area is focusing on the quay on the east part. During T500 storm surge, this part of quay would be flooded.

Front Harbor

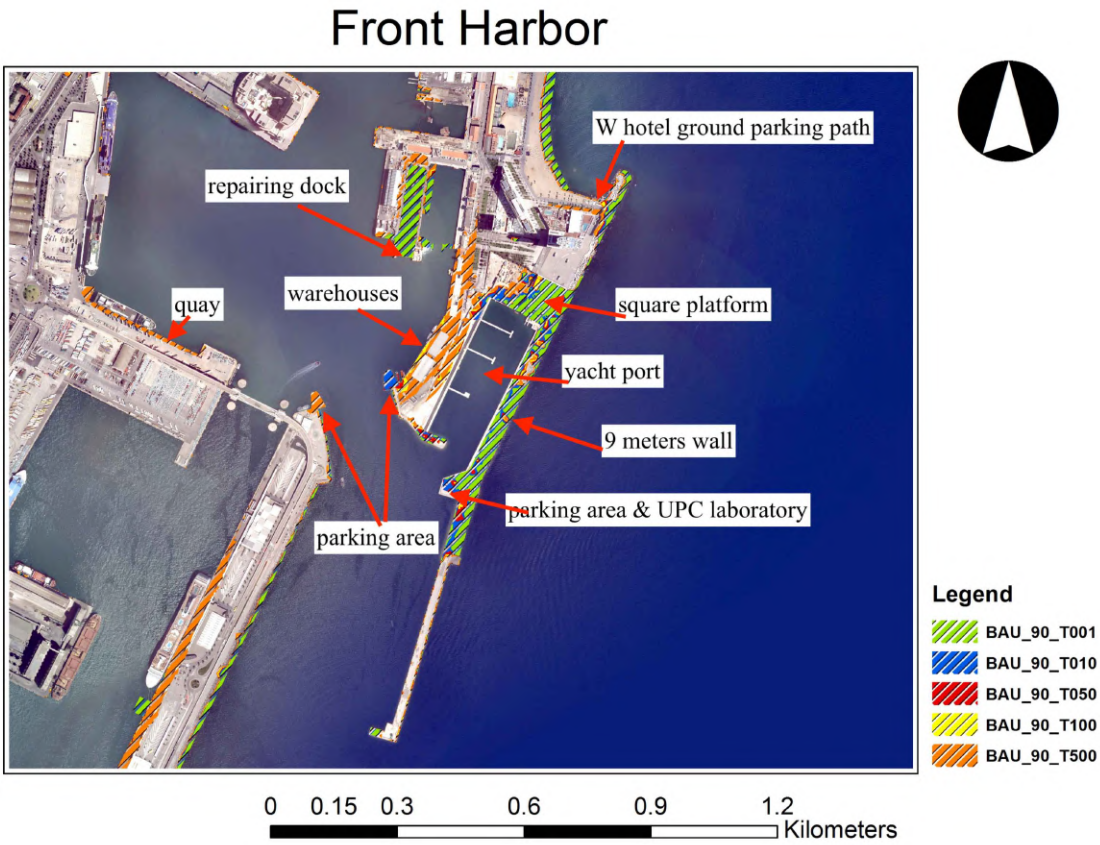

Figure 68. 90% SLR + Storm Surge projection at Front Harbor

The front harbor is still the most vulnerable place in the Barcelona coastal area. In the repairing dock, flooding situation in previous scenarios depends on its work status, but in this scenario, it would be flooded even if there is no ship in the dock during T500 storm surge. In the yacht port, according to the measurement in field trip, 3 piers would be flooded starting from T1 storm surge, the quays and two parking areas surrounding the port would be flooded starting from T1 storm surge as well. And the seawater can reach to two warehouses located on the west of port. The quay along the south part will be flooded as well during T500 storm surge. Besides, the pathway on the north which used for leading cars enter W hotel underground parking can be flooded starting from T500 storm surge because of the water height is already beyond the breakwaters which used for protecting the road. It seems like the front harbor will totally disappear during T500 storm surge if there is no adaptation.

As mentioned before, which is also applied in this scenario, the influence shows on the result map about breakwater on the east and the square platform located on the north of yacht port are not accurate. The breakwater already be built as an 9 meters wall and the square platform is also constructed a three floors building, hence, there is no more influence on these two parts.

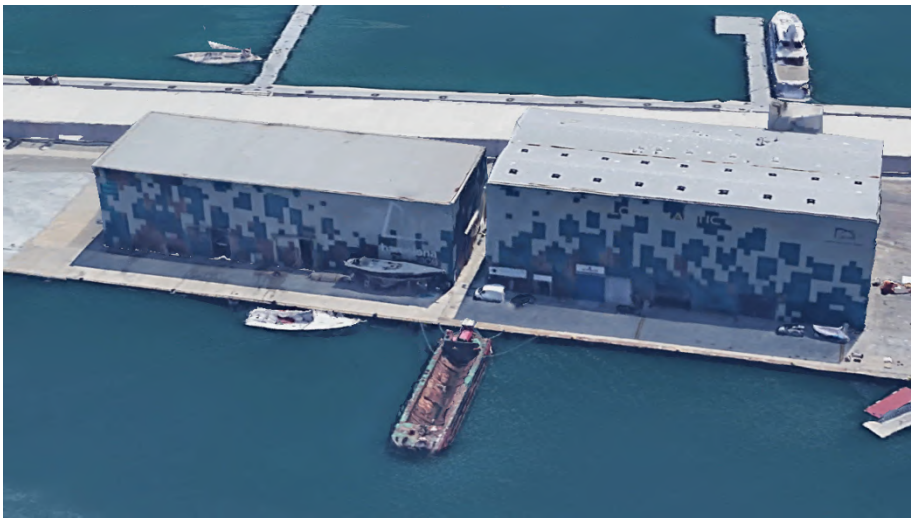

Figure 69. Warehouses located on the west of yacht port

Figure 70. Pathway leading to the W hotel underground parking area

Barcelona Harbor

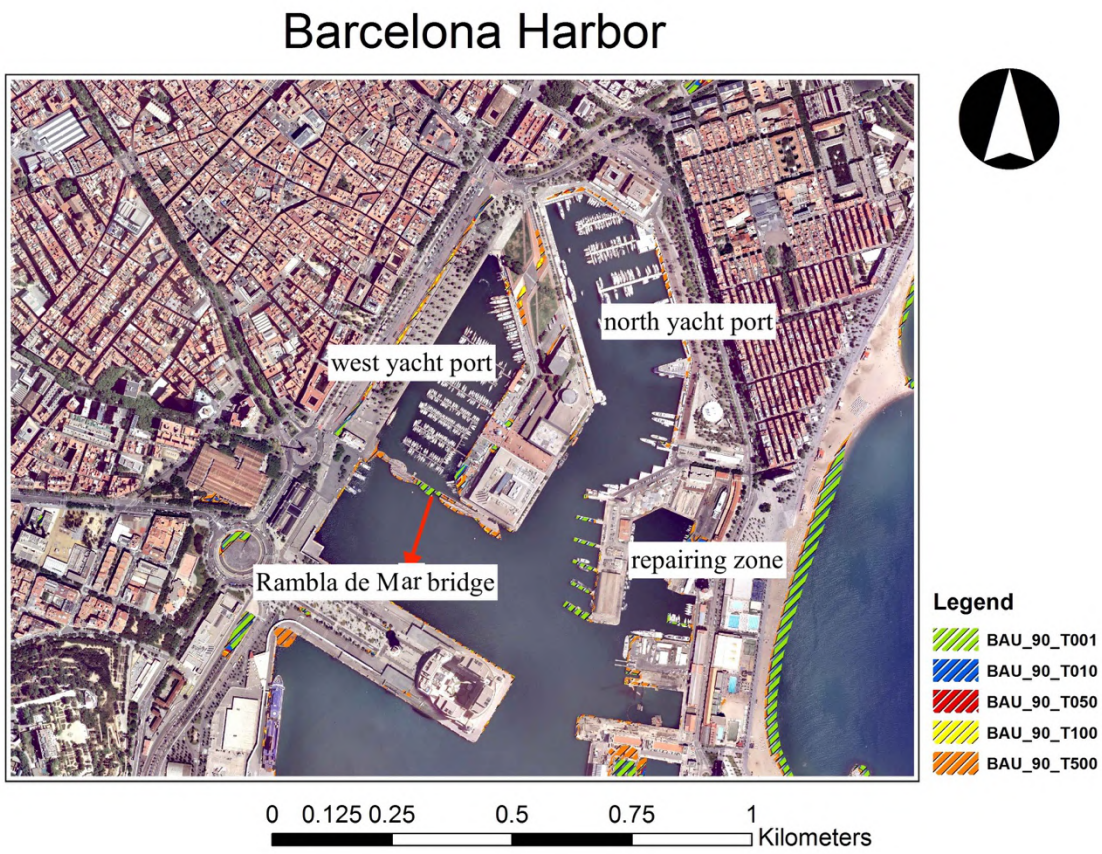

Figure 71. 90% SLR + Storm Surge projection at Barcelona Harbor

Two small yacht ports in this area all would get influences in this scenario, as well as the repairing zone.

The quay in the west yacht port would get influence starting from T1 storm surge, the quay in north yacht port would get influence during T500 storm surge. The tourist bridge Rambla de Mar can get influence in this scenario, from T100 storm surge, the water height will higher than 1.5 meters, that can reach to the first layer of bridge. The repairing zone also has big influence, besides the piers inside would be completely flooded starting from T1 storm surge, the two repairing docks will be covered by water starting from T10 storm surge.

In this area, most of them belongs to private properties, such as the north yacht port is parked full of the private yachts and sailboats and the repairing zone. Some of them provide services to tourist, for instance, the west yacht port, the Rambla de Mar bridge and the shopping mall

located at the end of the bridge. In the history, this area is where the old harbor located, and now It has become the most concentrated place for tourists. Hence, the physical damages in this area would cause huge economic losses and cultural losses, the impacts not only on citizens but also a large number of foreign tourists.

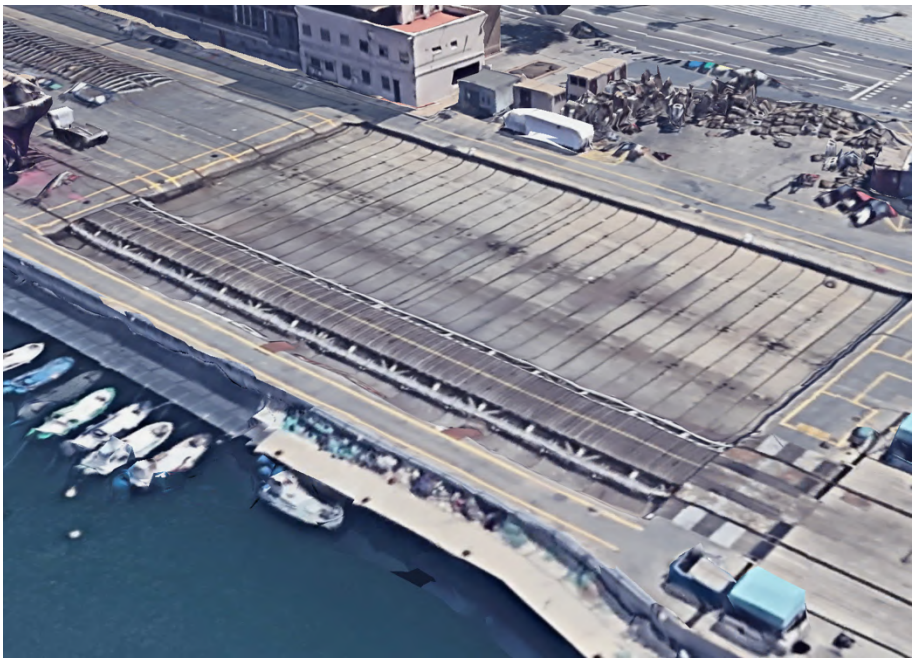

Figure 72. Satellite image of one of the repairing docks in the repairing zone

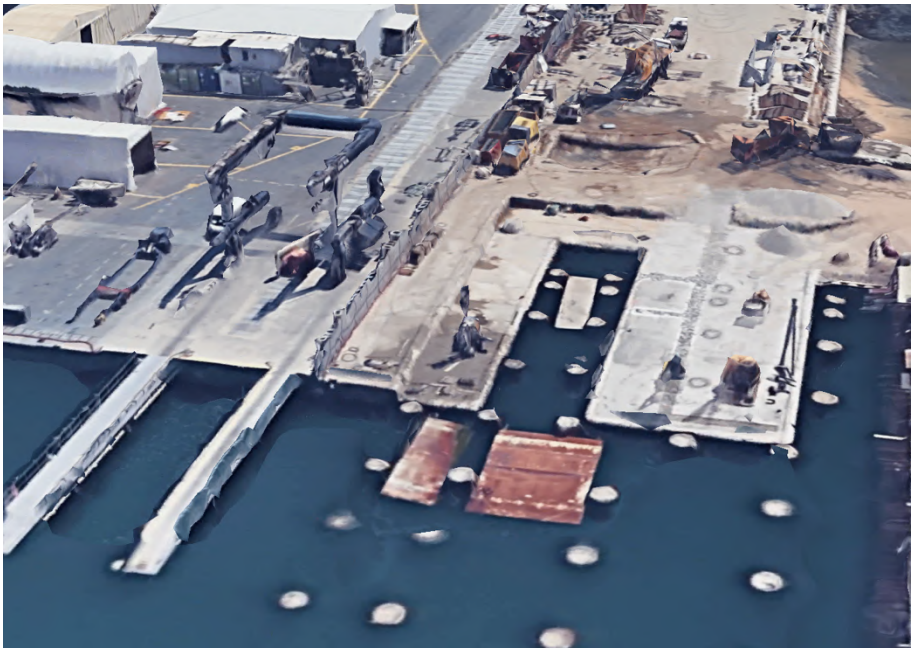

Figure 73. Satellite image of one of the repairing docks in the repairing

Barceloneta Beach Group

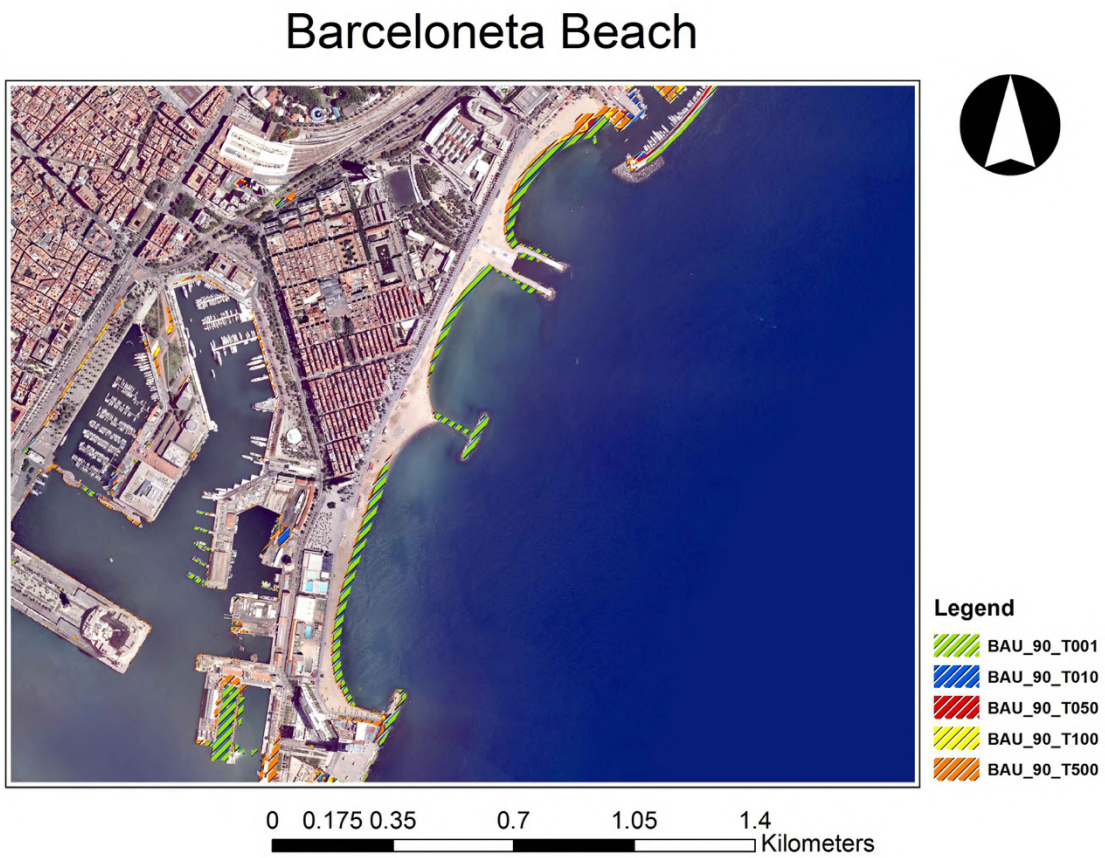

Figure 74. 90% SLR + Storm Surge projection at Barceloneta beach group

The first part of beaches would shrink its width by water around 23 meters to 28 meters on average from T1 to T500 storm surge; on the second part of beaches, the width of influences are about 18 meters to 22 meters on average in different storm surges; the last one would be flooded about 25 meters to 37 meters on average. The breakwaters separating the first and the second part of beaches, and the one located at the most north part in this area would be fully covered starting from T1 storm surge.

Olympic Harbor

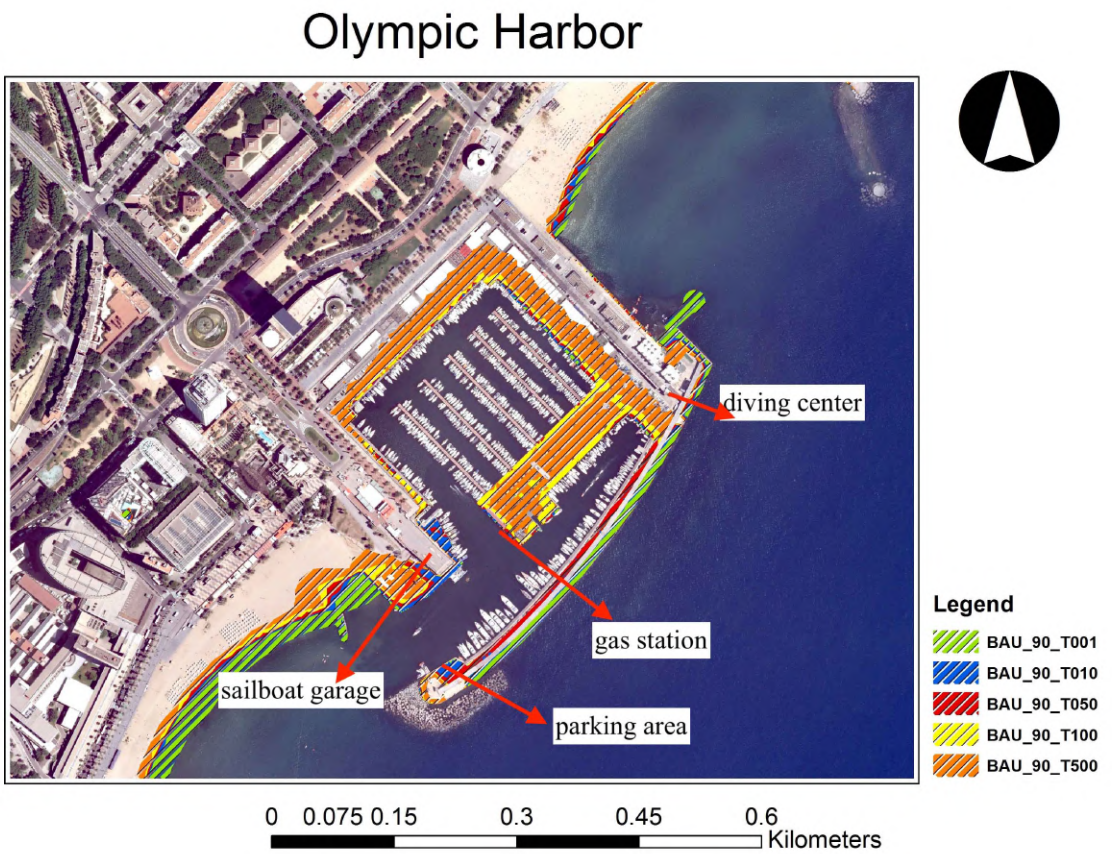

Figure 75. 90% SLR + Storm Surge projection at Olympic Harbor

This harbor also faces the huge threaten in this scenario.

The sailboat garage would get influences starting from T10 storm surge, and would be fully flooded during T500 storm surge. The restaurant next to it also would be fully covered by water. From T50 storm surge, the quays surrounding the harbor is starting getting influence, and the all of them would be fully covered during T500 storm surge. On the other side, the quay next to the parking area can get influence from T10 storm surge, and it would be fully flooded starting from T50 storm surge. The steps on the other side of the quay would fully covered by water starting from T10 storm surge. And the parking area, due to it has the same elevation as the quay, would also be fully flooded staring from T50 storm surge. The most vulnerable part, gas station would be flooded starting from T1 storm surge. The slope platform between diving center and sea has influence in this scenario, the water at most can invade inland for 36 meters, it even can reach to the building.

As we can see from the picture above, as the same as the Front harbor, Olympic harbor will be totally destroyed if there is no adaptation in this area.

Figure 76. Satellite image in the diving center and its slope platform

Figure 77. The slope between diving center and the sea

Nova Lcaria Beach

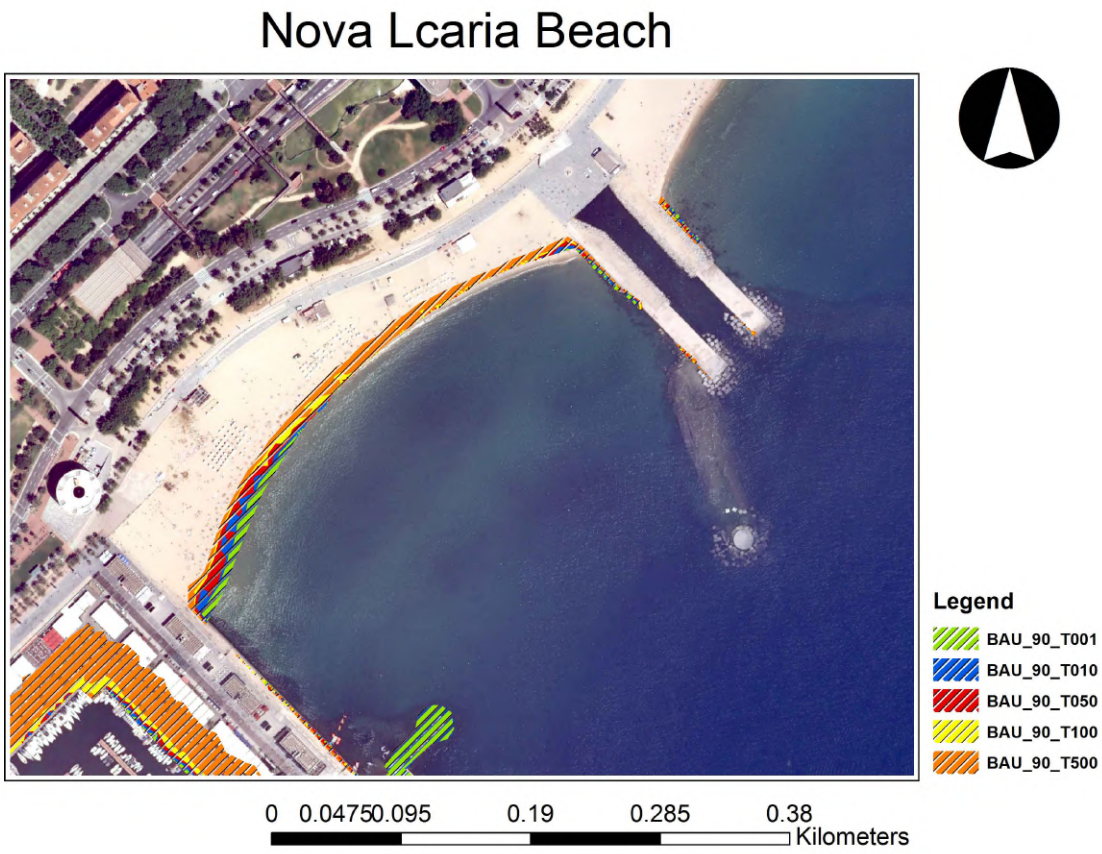

Figure 78. 90% SLR + Storm Surge projection at Nova Lcaria beach

The influence on this beach is from 7 meters to 20 meters on average in different storm surges.

Llevant Beach Group& Océanos Buceo Profesional

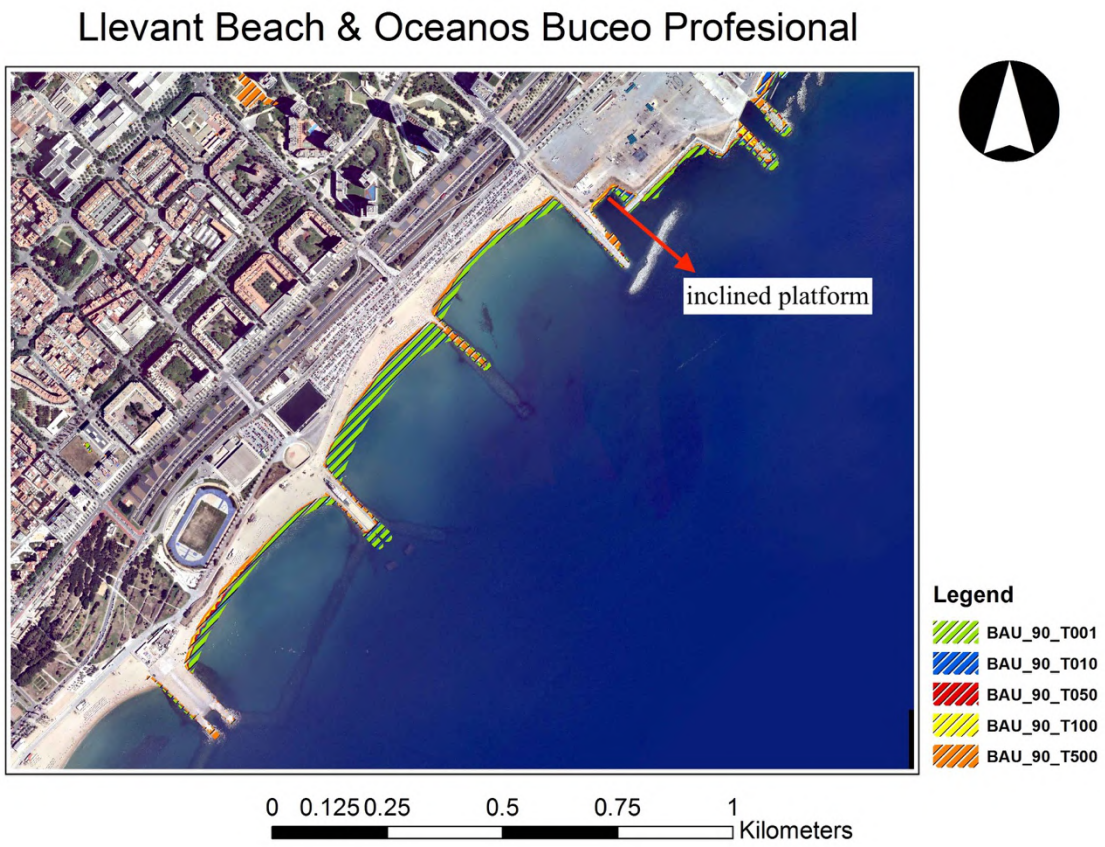

Figure 79. 90% SLR + Storm Surge projection at Llevant beach & Océanos buceo profesional

In this part, the most vulnerable part is still the middle part of the beaches. The maximum width of influence on it during T500 storm surge is about 50 meters, the first and the third part are about 30 meters. There are two breakwaters would be fully flooded starting from T100 storm surge. The inclined platform on Océanos Buceo Profesional has influence about 20 meters on average during T500 storm surge.

Fòrum Swimming Zone & Fòrum Harbor

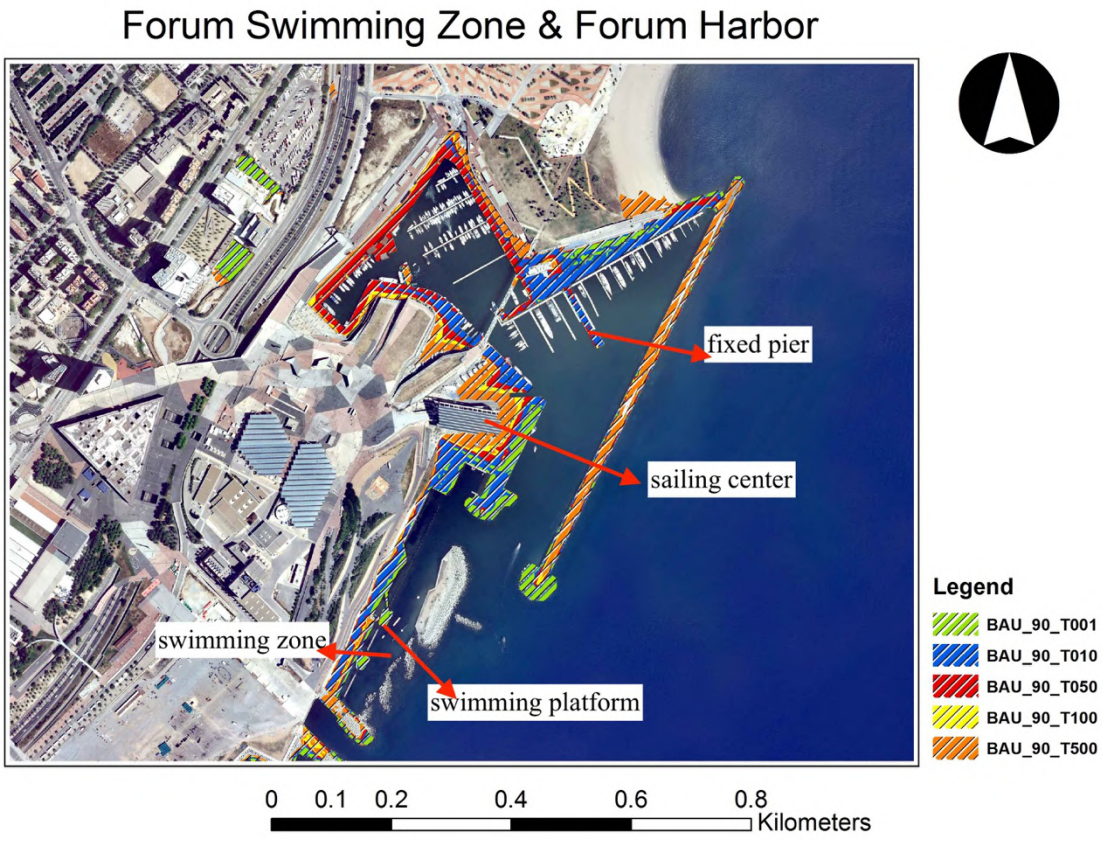

Figure 80. 90% SLR + Storm Surge projection at Fòrum swimming zone & Fòrum

Still, this area is the most vulnerable place on the coast.

At the swimming zone, the swimming platform would be flooded starting from T1 storm surge, the path along the sea will be fully covered by water starting from T50 storm surge. In the Fòrum harbor part, the sailing center platform, quays including the road behind it and one fixed pier will be flooded starting from T10 storm surge, and will be completely covered by water starting from T50 storm surge. And the fixed pier, due to has the same elevation as the quay, would be covered by water staring from T50 storm surge as well. That means from T50 storm surge, the whole harbor will be covered by water. The jetty on the east will be flooded during T500 storm surge.

Besós River & Litoral Beach

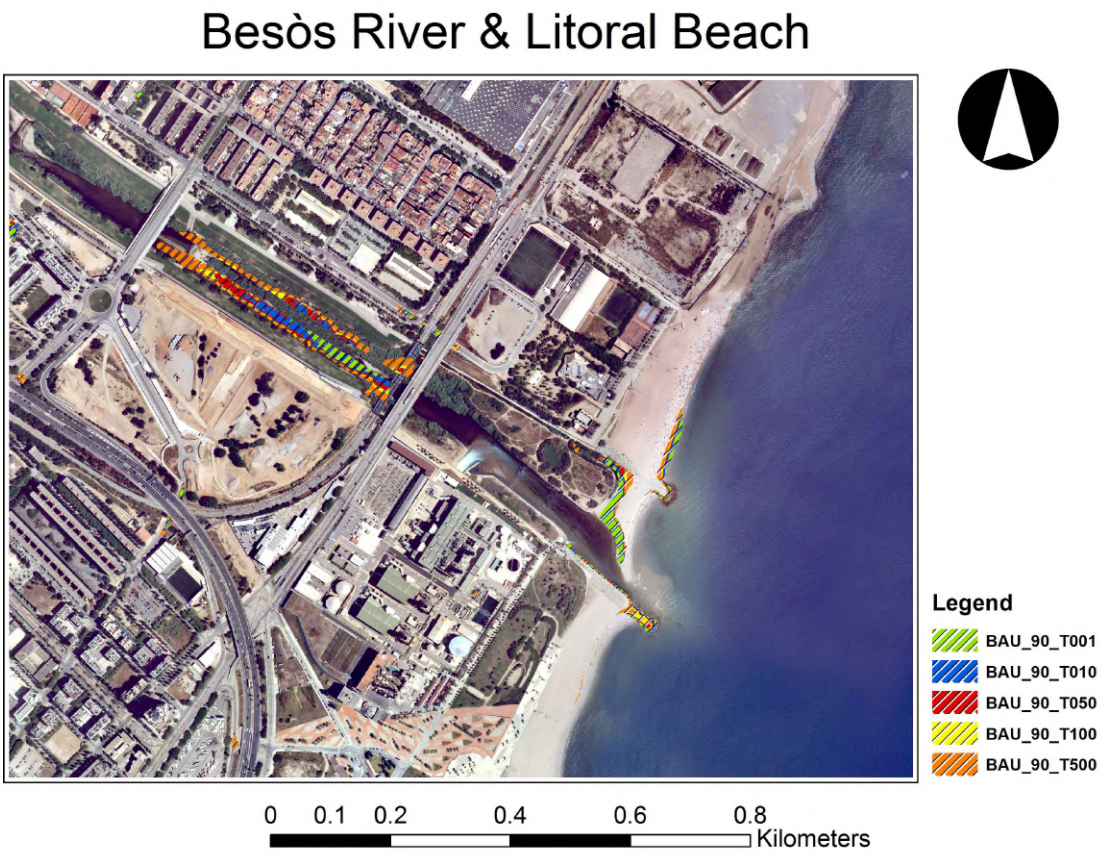

Figure 81. 90% SLR + Storm Surge projection at Besós river & Litoral beach

In this scenario, this part still in a safety situation compared to other places. The river bank cannot be influenced by the sea level rise and storm surge. The maximum influence on beach is around 15 meters. And one breakwater will be covered by water during T500 storm surge.

The invisible impacts on this part is important such as on ecosystem and boundary condition of the river. The more specific simulation about them and measurement of these kinds of influence need have to be done to specific the influence.

Summary

As the riskiest scenario in this thesis, the influence not only focusing on the part it was used to be in other scenarios, but also much more new parts have serious situation that cannot be ignored. Harbors are the most vulnerable places, especially in Olympic harbor and Fòrum harbor, the water will fully cover them if there has no adaptation to protect or update them. The influence on the beaches still notable, the most serious part has more than 50 meters influence width. Some new places such as tracks in the oil harbor, quays in the container harbor, W hotel ground parking and diving center in the Olympic harbor will start getting influence, which will cause new problem and damages in Barcelona.

The influence on different area shows in following table: if the influence is big enough to affect the components not being able to use anymore, the fonts is in red; if there is influence but can still operate properly, the fonts is in black; if there is a blank means there is no influence in that return period. (all the influences are based on result map corrected by field trip)

Table 8. Influence results in current scenario + each storm surge in each area

		T1	T10	T50	T100	T500
90% SLR + storm surge projection	**Estuary of Llobregat river**	beach	beach	beach	beach	beach
		green area	green area	green area	green area	green area
		breakwater	breakwater	breakwater	breakwater	breakwater
	Llobregat river	right river bank park	right river bank park	right river bank park	right river bank park	right river bank park
	Llobregat river left harbor	blank space	blank space	blank space	blank space	blank space
			small dock	small dock	small dock	small dock
		breakwaters	breakwaters	breakwaters	breakwaters	breakwaters
	Oil Harbor	8 piers	8 piers	8 piers	8 piers	8 piers
					track	track
						east quay
		south breakwater	south breakwater	south breakwater	south breakwater	south breakwater
		jetty	jetty	jetty	jetty	jetty
		west discharging platform	west discharging platform	west discharging platform	west discharging platform	west discharging platform

			north discharging platform	north discharging platform	north discharging platform	north discharging platform
	Container Harbor	breakwater	breakwater	breakwater	breakwater	breakwater
				quay	quay	quay
	Front Harbor	3 piers	3 piers	3 piers	3 piers	3 piers
		repairing dock*	repairing dock*	repairing dock*	repairing dock*	repairing dock*
		breakwaters	breakwaters	breakwaters	breakwaters	breakwaters
		2 parking areas	2 parking areas	2 parking areas	2 parking areas	2 parking areas
		quay inside the yacht port	quay inside the yacht port	quay inside the yacht port	quay inside the yacht port	quay inside the yacht port
					quay	quay
					warehouse	warehouse
						pathway
	Barcelona Harbor	7 piers	7 piers	7 piers	7 piers	7 piers
					bridge	bridge
		quay in the west yacht port	quay in the west yacht port	quay in the west yacht port	quay in the west yacht port	quay in the west yacht port
						quay in the north yacht port
			repairing docks*	repairing docks*	repairing docks*	repairing docks*
	Barceloneta beach group	beach	beach	beach	beach	beach
		north breakwater	north breakwater	north breakwater	north breakwater	north breakwater
		middle breakwater	middle breakwater	middle breakwater	middle breakwater	middle breakwater
	Olympic Harbor	step	step	step	step	step
			quay next to the parking area	quay next to the parking area	quay next to the parking area	quay next to the parking area
		gas station	gas station	gas station	gas station	gas station
			parking area	parking area	parking area	parking area
			sailboat garage	sailboat garage	sailboat garage	sailboat garage

				quay inside the harbor	quay inside the harbor	quay inside the harbor
	Nova lcària beach	beach	beach	beach	beach	beach
	Llevant beach & Océanos Buceo Profesional	breakwaters	breakwaters	breakwaters	breakwaters	breakwaters
		inclined platform	inclined platform	inclined platform	inclined platform	inclined platform
		beach	beach	beach	beach	beach
	Fòrum swimming zone & Fòrum harbor	swimming platform	swimming platform	swimming platform	swimming platform	swimming platform
		jetty	jetty	jetty	jetty	jetty
			fixed pier	fixed pier	fixed pier	fixed pier
				swimming zone path	swimming zone path	swimming zone path
		sailing center platform	sailing center platform	sailing center platform	sailing center platform	sailing center platform
		quay	quay	quay	quay	quay
		road behind the quay	road behind the quay	road behind the quay	road behind the quay	road behind the quay
	besós river & Litoral beach	beach	beach	beach	beach	beach
		breakwaters	breakwaters	breakwaters	breakwaters	breakwaters

*Note: * means its flooding situation depends on its status.

Correction based on reality

Due to the digital elevation model used for simulation in CMIP 5 modes are not the latest version, and some of places along the Barcelona coast still under construction. There are some locations need to be remeasured as for getting a more accurate result. All of the correction is all taken into consideration during the analysis above. This section is a summary of all of the correction mentioned before.

For the purpose mentioned above, the author took three days walking along the most coastal area in Barcelona to remeasure the elevation that may have doubts. The field trip was expected to measure all the coastal area, however, since some places are not allowed to enter in and some of them cannot reach to because of there is no transportation, only Front harbor, Barcelona harbor, Olympic harbor and Fòrum swimming zone & Fòrum harbor are remeasured during the field trip. According to the measurement, most of area are more or less the same with digital elevation model. The differences will be described following:

Front Harbor

In the front harbor, there are three location need to update its digital elevation model.

Firstly, the breakwaters on the east. According the result map in each scenarios, this part will be fully flooded during some storm surges. However, there already constructed a nine-meter wall which used for blocking sea water on the east side and storage on the west side. Hence, in along all the breakwater in this part could not be flooded in every scenario.

Figure 82. Nine-meter wall along the sea

Figure 83. Three-floor building located on the north of quay in the yacht port

Secondly, the square area located between yacht port and W hotel. It shows that this place is easily get flooded in different scenarios. But according the field trip, this place already built a third-floor building for parking commercial activities and parking. Hence, the water at most can reach to the quay but could not invade into this square area.

The last one is 3 piers inside the yacht port. According to the result map, they have no impact from sea level rise. However, actually, the piers inside the yacht port is made by concrete and fixed on the quays. They almost have the same height around 0.8 meters, that is, 3 piers will get flooded when the quay are flooded.

Figure 84. Fixed pier in the yacht port

Besides the measurements mentioned above, there are more locations that has doubts need to be checked, such as repairing docks inside the repairing factory. According to the results map, in every scenario, they all showing that it would be fully flooded starting from T1 storm surge. However, according to its special function, its flooding situation should depend on its working status. But this place is not allowed people enter in, the writer cannot have an accurate judgement of accuracy of these places' elevation.

Figure 85. Satellite image of the repairing dock in the Front harbor

Barcelona Harbor

There is one place need to be corrected in this area, the tourist bridge Rambla de Mar.

The design of the bridge is artistic, using waves and interlaced designs to show the shape of the water. According to the results map, the lowest part of these bridges will be submerged in the case of some storm surges, but according to field measurements, even the lowest part of the bridge deck is about 1.5 meters from the water surface. It will not be flooded under most projections, so it should be an error in the digital elevation model.

Figure 86. Rambla de Mar bridge in the Barcelona

Figure 87. Wood piers in the west yacht port of Barcelona

Additionally, the author validated the piers inside the yacht port all made by woods, which means they can float on the water; hence, they cannot be flooded. However, due to the yacht port is one of the tourism part, it is not allowed people enter inside without ticket, the measurements on the quays cannot be gotten. Besides the yacht port, the place inside repairing factory is not allowed to enter as well, therefore, author could not get the measurements.

Other places

Except the front harbor and Barcelona harbor, the digital elevation model can represent the elevations in the Olympic harbor and Fòrum swimming zone & Fòrum harbor accurately, there is more or less no difference between reality and digital elevation model. Therefore, the results in these two parts are reliable.

Figure 88. The yacht port in the Fòrum harbour, according to the measurement, the elevation of the quay along the port is about 1.2 meters, this is similar to the elevation reflected from the results map.

Figure 89. The yacht port in the Olympic harbour, according to the measurement, the elevation is similar to the elevation reflected from the results map and all the piers here are made by wood.

Future expectation

Actually, there are still a lot of places that need to be double checked but could not be done due to many reasons. Some of impacts we could not find out the reason but just

For example, in Llobregat river estuary, the green space has the most severe situation as shows in the results map, through this result, a reasonable assumption is that here has low elevation and special surface morphology, the impact from groundwater rising and submerge the green space. But because of this “low elevation” assumption could not validate through reality; the accuracy of this part is not that clear.

Due to the results map just shows there will be an influence only if the elevation is lower than the water level, as it shows in the images, many places inside the city shows the flooding as well. But this kind of flood apparently are not coming from the sea, because between these floods and sea there are hundred even thousands meters difference. the assumption that can make under this result is they all impacted by the groundwater, which can rise up following sea level rise. However, this assumption is depending on whether there is a way that between the location and the groundwater that water can enter in, whether the morphology allows groundwater to penetrate and whether the permeability of this place can allow the same height water penetrate in a short period during the storm surge and, all of these need check or measurement. The track places right behind the quays in the oil harbor also have the same problem.

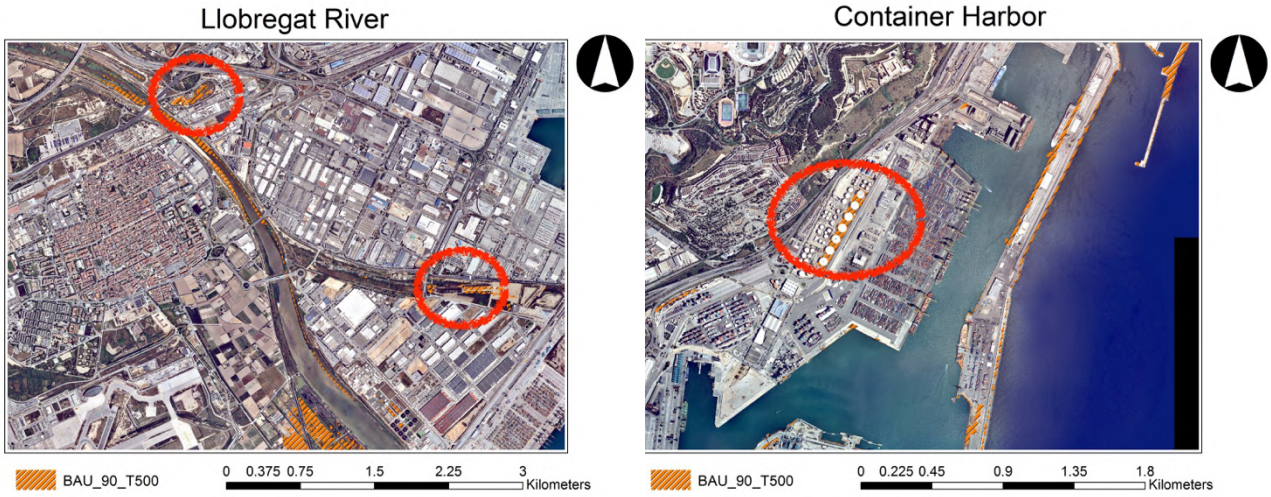

Figure 90. The impacts on the inland of in Llobregat river and container harbour in 90% SLR+ Storm Surge projection

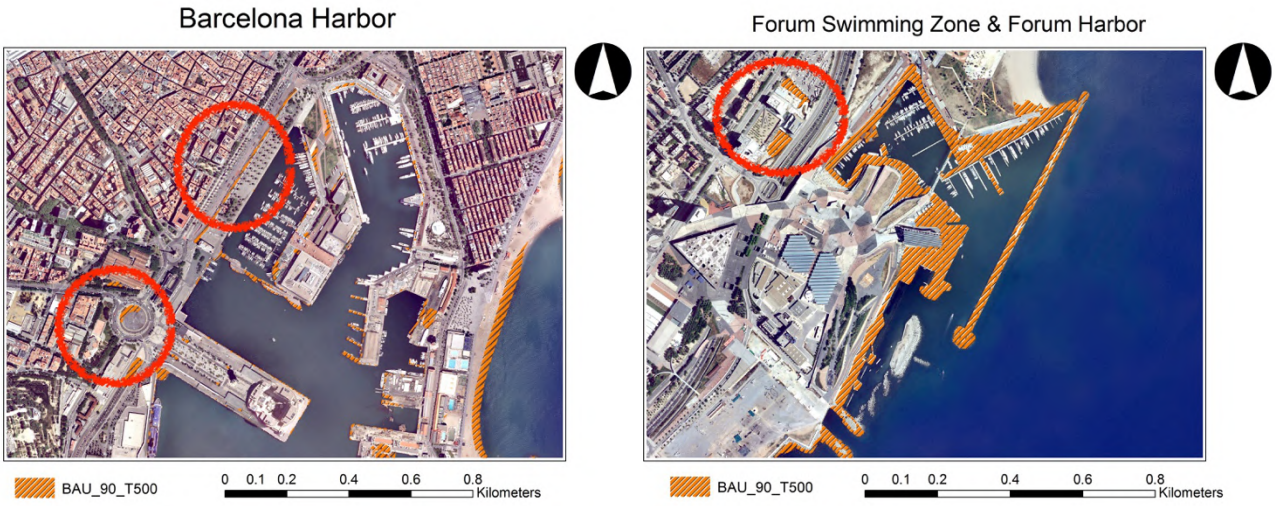

Figure 91. Figure. The impacts on the inland of in Llobregat river and container harbour in 90% SLR+ Storm Surge projection

There are some places not allowed going inside such as repairing factory, private yacht port and yacht port for tourist etc. in these places, the author cannot do the measurement.

All in all, it needs the latest digital elevation model if we want to have more accurate results. It is better to have all type of land to know if they are easily getting influence from groundwater. And the relationship between ground to groundwater also need to be clear, it can help researchers to know which part of facilities or infrastructures can get influence due to the ground water rise up caused by sea level rise.

Impacts summaries

Obviously, the consequence from sea level rise can lead to a variety of impacts, not only the physical influences on the coastal areas as the previous analysis, but also the potential impacts, including in the economy, tourism, heritage and culture protection, ecosystem and agriculture, etc. The following thesis will analyze the direct and indirect impacts from sea level rise in these aspects on river, coastal area and city.

River

Direct impacts

There are two rivers located in the study area: Llobregat river on the west and the Besós river on the east. The direct impact on Llobregat river is focusing on the right river bank park. In the scenarios with storm surges, this part would be flooded. The risk that water can enter into inland is notable. Luckily, the water cannot cross the park to reach the inland, the only thing would get influence is it is no more suitable for citizens visiting or jogging during the extreme storm surges, it is better to set up a warning signal in this area to reduce unnecessary human injury. However, in the Besós river, there is no direct damages on the river, the impact polygons showed in the results map are located on the plants. The river banks can protect both sides perfectly in all of scenarios.

What's more, with the sea level rise, the salty water would enter into river from estuary, and it causes two main problem. On the one hand, the biological and chemical elements in the salty water is different from the water in the rivers. Hence, this would destroy the ecosystem in the river. On the other hand, the sea level rise also would change the downstream level of the rivers, which changes the downstream boundary condition in hydraulic models. This is able to change river dynamic performance. Of course, the it also depends on the critical depth of the rivers, if the downstream boundary condition higher than critical depth, it may cause the more intense and more frequent river flooding.

Potential impact

According to the flooding occurs at the right river bank in Llobregat river, besides setting up warning signal along the river bank, updating this park also a good choice, such as building dikes along the park. According to (Jochen Hinkel, 2013) declared in the paper that the cost of dikes in not only depends on the expose area, but also population density and GDP per

capita since the richer the world is, the higher the safety and protect level requirement need to be considered. This updating would cost the necessary economic losses.

Coastal area

Direct impacts

According to the analysis, the most vulnerable places are focusing on coastal, including green spaces, harbor and beaches.

The intrusion of sea water would cause the erosions on the coastal area. For instance, when the salty water flood on the quays, roads, breakwaters and piers the infrastructures located on this area would get a slowly erosion. For green spaces where can be invaded by salty water, it may cause the lost and changes of the lands to destroy the plants on this area. For the ponds, the salty water enter into the surface water would lead to the salinization.

Potential impacts

In order to resist seawater intrusion, some necessary measures have to be done. For example, building and maintaining the coastal defenses and updating breakwaters. These kinds of adaptation should be done before serious event coming. But if the extreme events already caused damages before adaptation, the rebuilding or repairing of all kinds of facilities and infrastructures need to be taken into consideration. All of these cause economic losses. Or there is another way, moving all of the existing infrastructure back to the inland. Even if it sounds exaggerated, but it seems that it is necessary for those beaches that have a lot of reductions to maintain their attraction and the ability to accept tourists. With no doubts, it would cost a lot of money as well. If ignore the impacts on the beaches, the relevant departments have to bear the economic losses in tourism.

City

Direct impacts

Even if the sea water cannot enter into city directly, it can enter along with groundwater. With the increasing of the sea level, the groundwater table would arise as well. The facilities containing groundwater or the underground infrastructures would be influenced by salty water salinization and cause erosion problem. For instance, the water network system, storm water tanks, gas network systems, building foundation and transportation tunnels, etc. would have erosion or seepage problems. In the water treatment plan, due to the new elements enter

into it, the ecosystem in water system would totally different. During the depuration processing, it is able to need a new chemical reaction to clean up water. The well water pollution also notable, for example, pumping activities from wells is providing water resources to the garden watering, irrigation and street cleaning now. All of these will end to reach to the sewer system, it would also pollute the water in water treatment plan.

Potential impacts

In Barcelona, pumping activities used for industries in 80s to 90s, but it decreased after the factories moved away from the city. However, some pumping activities have to be implemented because of the serious seepage problem in Barcelona city. Due to the groundwater table rising up, the urban flood would increase the risk in vulnerable places. Because of the shortening of the distance between the surface and the groundwater surface, urban flooding would become very serious in areas with high groundwater levels. Hence, pumping activities have to implement to maintain the water table.

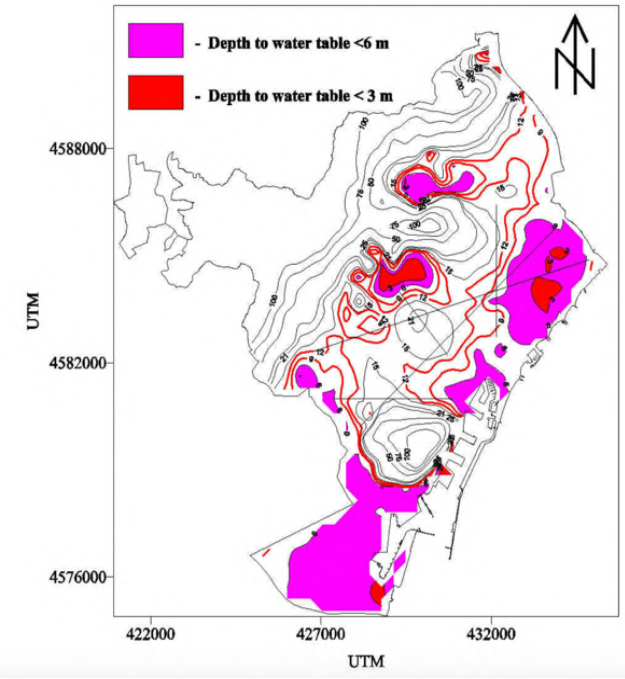

Figure 92. Depth from ground surface to ground water table (1996)

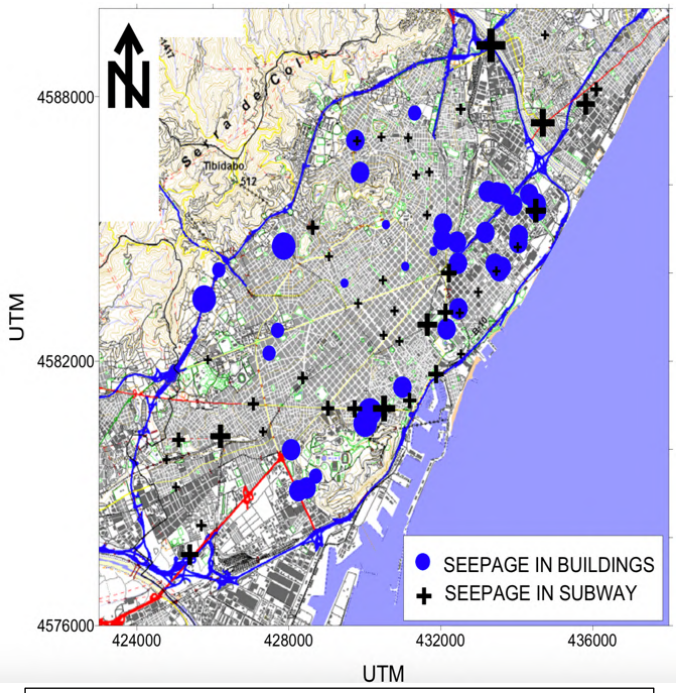

Figure 93. Seepage problem in Barcelona city. (Symbol size proportional to amount of seepage)

An important portion of the metro system and many buildings were built during the period 1950-1975, coinciding with the period of maximum water level depletion. At that time, neither designers nor constructors were aware that groundwater levels could recover to the past levels. Thus, metro system has to pump around 10 -15 million m^3 per year to drain the

tunnels and, in addition, 5 million m^3 per year are pumped from railway tunnels (VÁZQUEZ-SUÑÉ, 2003). In the end of last centery, the total amount of water that was being pumped from the metropolitan metro is about 12 million m^3/year. The problem is not restricted to a few points, but is quite general.

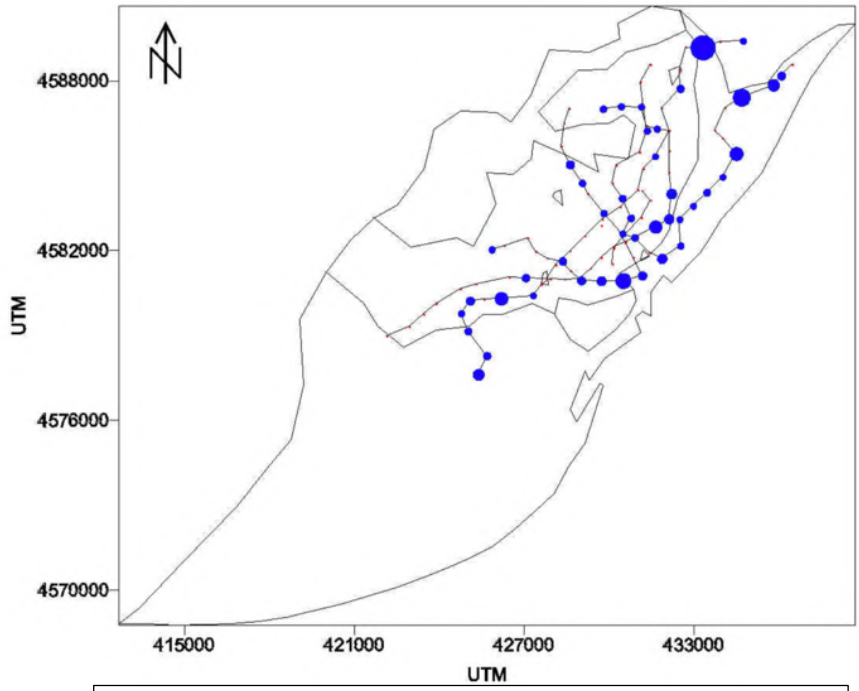

Figure 94. Location of seepage problem in metro system. (symbol size is the proportional to seepage)

All of these seepage problem would lead to an economic problem. It needs money to do the pumping activities, repairing, upgrading the infrastructures. Besides that, when an extreme event occurs, no-functioning metro system caused by the seepage problem also can cause amount of economic losses.

Discussion

Study Limitation and Suggestion

This thesis just gives a simple analyzed about the physical influence based on the results map which produced by the CMIP5 models simulations. As the CMIP5 models, there are 10 models used for simulating projections. However, for sea level rise projection, there are only 9 models can be used because one of the models BCC-CSM1-1 has a great opposite results compared to other 9 models. Besides, these 9 models result also have different unignored uncertainties. It needs more advanced models to improve the simulation results, actually the community is continuing developing new models for more accurate projection, for instance, CMIP 6 has been created and it can address a large range of specific questions and fill the scientific gaps of the previous CMIP phases.

Secondly, the data used in this models are limited. On the one hand, the digital elevation model need update based on the field trip. On the other hand, the base line data are not totally coming from the reality collection. Because the observed data of sea level only can be collected from 1993 to 2016, the data has extended to 1986 to 2015 by using downscaling methods. Additionally, all the observed data came from only one measurement buoy. It also caused a big uncertainty. Even if there is already no way to collect the history data, something we can do is building more new collection station or buoy to help future study.

Last, the analysis in this thesis only focusing on physical influence, but the impacts caused by sea level rise are not only simple physical damages, but also including besides that, including economic losses, ecosystem damages, even human safety risk. More simulation such as chemical elements changing in ground water after sea level rise, hydraulic simulation on two rivers in Barcelona, micro-economy impacts simulation, etc. have to be done in more aspects analysis for a comprehensive understanding on damages caused by sea level rise.

Conclusion

All in all, according to the analysis, the scenarios only included sea level rise projection have much more moderate impacts compare to the scenarios contain storm surges.

Thus, it can be positively believed that the sea level rise does not have much impact on Barcelona in 2100. But the impact of the storm surge has to be considered, some necessary adaptations still need to be implemented.

What's more, according to the analysis results, the most vulnerable areas are located in harbors, including Front Harbor, Barcelona Harbor, Olympic Harbor and Fòrum Harbor. During the most extreme storm surge events, water would cover the whole harbor if there are no on-time adaptations. From the perspective of rivers, the area of influence at the Llobregat river estuary is the largest. Although it is only a useless green space, it is worthy to give an alarm about the huge changes on this area from seawater intrusion. For the beaches, the beach located on the Llevant beach group would receive the most severe seawater intrusion. The sea level rise in Barcelona will not only cause physical damage to the coastal areas, urban and rivers, but also potentially cause economic losses from the declination of tourism and pumping activities. In order to avoid more damages, some adaptation have to be done. The relatively safe areas include Container Harbor, Bagatell Beach and Fòrum Beach. From the results map, sea level rise and storm surges do not have any impact on these places.

In addition, more detailed influences require more hydraulic or hydrological simulations to specify. For example, the dynamic performance of rivers after rising up sea level and the pollution situation in water treatment plants. These researches need a further studies.

At last, the report declared that Sea level rise is generally badly simulated by the climate models for Barcelona, even after the bias correction. Only a few models passed most of the statistical test. Therefore, results of sea level projections should be taken with great caution. Because of this, more accurate and reliable models need to use for simulating sea level rise projection in the future.

References

Anon., n.d. *RCP database.* [Online]
Available at: http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=welcome

Center of Climate Adaptation, 2019. *climate change post.* [Online]
Available at: https://www.climatechangepost.com/netherlands/coastal-floods/
[Accessed 3 June 2019].

Fernández, F. a., 2016. Sea level rise scenarios in the peninsular Spanish tide gauges in the year 2100. *EstudiosGeográficos,* pp. 57-79.

Jochen Hinkel, D. L. A. T. V. M. P. R. J. N. R. S. J. T. B. M. X. F. C. I. a. A. L., 2013. Coastal flood damage and adaptation costs under 21st century sea-level rise. *PNAS.*

Montañés, 2012. *Variaciódelnivell del mar a la PenínsulaIbèricaduranl'últimsegle.* [Online]
Available at: https://ddd.uab.cat/pub/trerecpro/2012/hdl_2072_204198/PFC_JoanPascualMontanes.pdf
[Accessed 2 August 2019].

NASA, 2019. *Global climate change.* [Online]
Available at: https://climate.nasa.gov/vital-signs/sea-level/
[Accessed 3 June 2019].

National Geographic , 2019. *Sea level raise, explained.* [Online]
Available at: https://www.nationalgeographic.com/environment/global-warming/sea-level-rise/
[Accessed 3 June 2019].

Pfeffer, H. O., 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science,* pp. 1340-1343.

R. Monjo, C. P. E. G. D. R. C. P. J. P. L. T. B. R. M. V. L. P. S. V. L. M. D. M. M. J. R., 2018. *Deliverable D1.3 report on extreme events prediction,* barcelona: s.n.

R. Monjo, J. E. G. D. R. C. P. C. P. L. T. J. R. B. R. M. V., 2017. *Deliverable D1.2 Final climate scenarios report,* s.l.: s.n.

R.Monjo, J. M. B. A.-H. L. A. E. R. J. R. S. C. C.-L. I. J. L. M. S., 2016. *Deliverable D1.1 Data collection and quality control. summary of studies on climate variables at the research cities,* Barcelona: s.n.

RESCCUE, 2019. *RESILIENT CITIES FACING CLIMATE CHANGE*. [Online] Available at: http://www.resccue.eu/resccue-project

Serra C., B. A. L. X., 2001. Analysis of maximum and minimum daily temperatures recorded at Fabra Observatory (Barcelona, NE Spain) in the period 1917-1998. *nternational Journal of Climatology,* pp. 617-636.

Tsimplis MN, R. M., 2002. Sea level in the Mediterranean Sea: The contribution of temperature and salinity changes. *Geophysical Research Letters,* pp. 51-54.